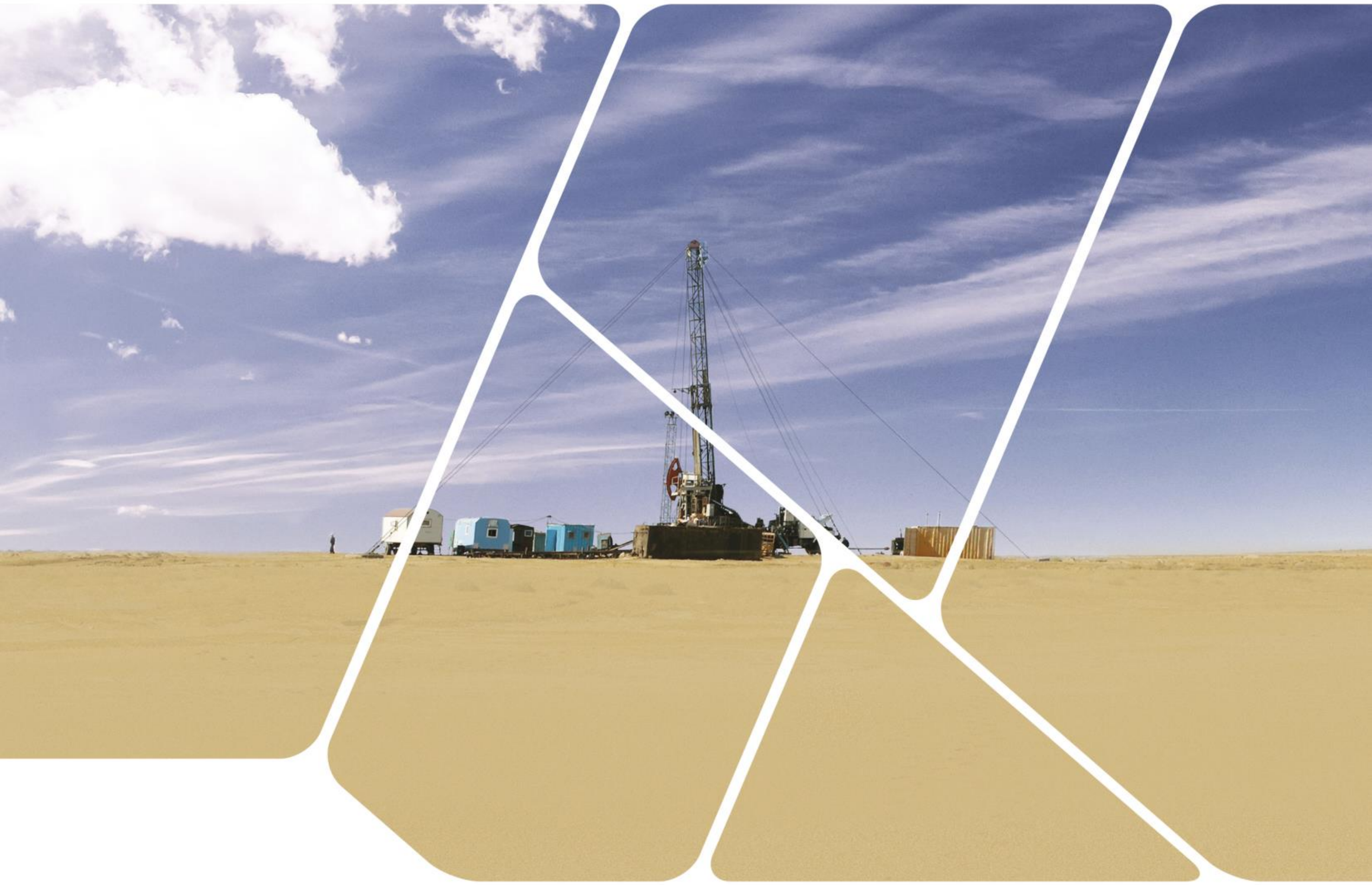


W1 : Petroleum Geosciences – Fundamentals of Basin Exploration

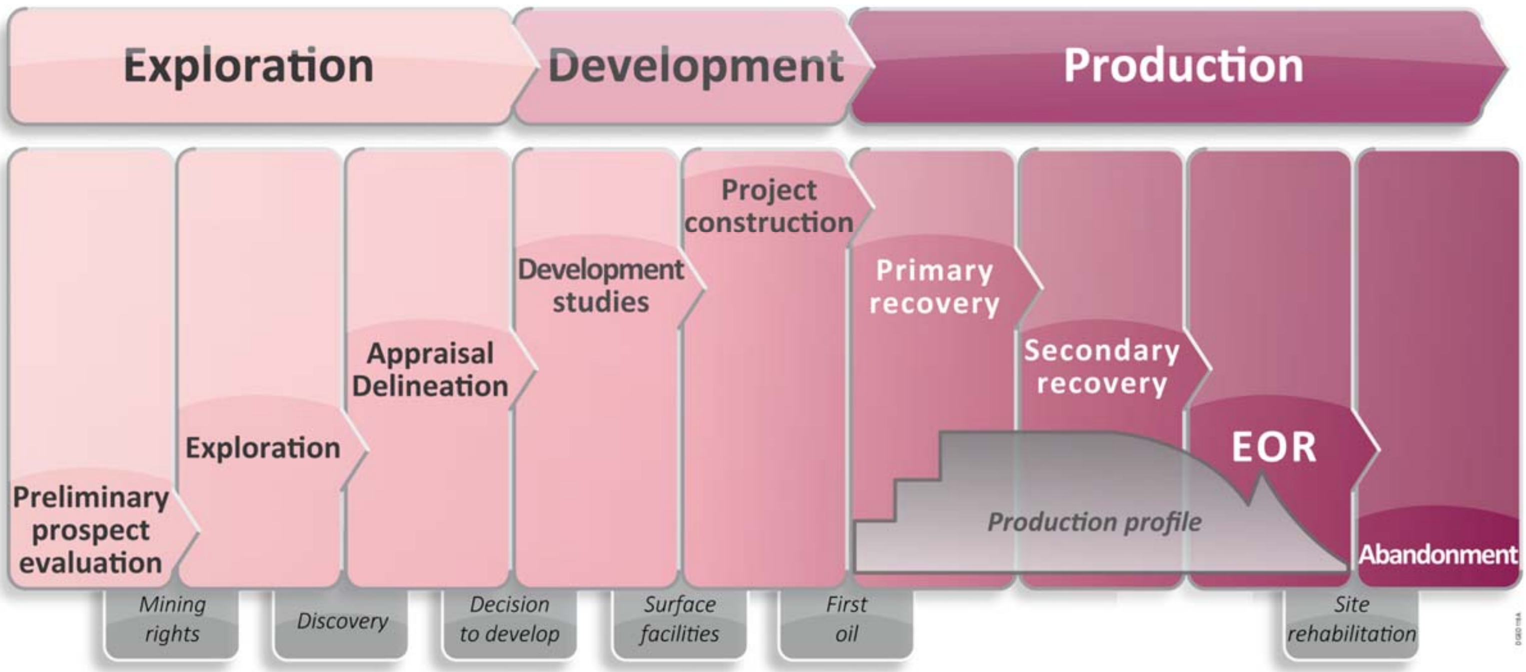
Formation certifiante en Management de la chaine de valeur de l'EP et Ingénierie pétrolière – *Du 06 Novembre au 10 Novembre 2016*

Fundamental basin exploration workshop

Arnaud Torres, Jacques Kuchly

IFP Training

The E&P workflow



Sommaire

Exploration-Production: stakes and challenges

1. Where are hydrocarbons?

- In reservoirs (porous or fractured)
- How did they get into reservoirs?
- Where are they coming from? (source and generation)
- Why are they accumulated in this trap?

Basin analysis

- Elaboration of exploration concept → play assessment
- Identification of prospects
- Evaluation of uncertainties and risks
- Exploration well → OOIP calculation

Exploration strategy

2. How to produce them?

- Geological reservoir model (static)
- Quantification of reservoir characteristics
- Identification of heterogeneities
- Dynamic reservoir model
- Production prediction
- Appraisal well positioning

Strategy and design for

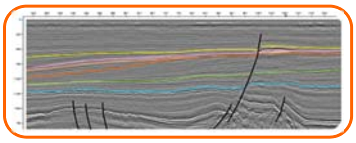
Field development

Structural & stratigraphic analysis: data & tools

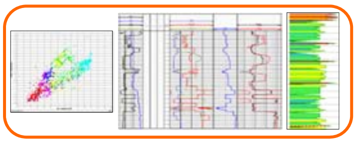
Steps 1&2

DATA

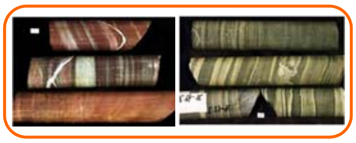
Seismic
- Structural framework
- Basin infill geometry



Log
- Lithology, mineralogy
- Electro-facies analysis

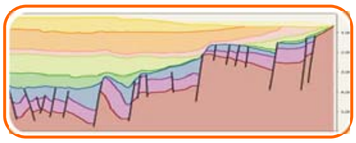


Core
- Litho-facies identification
- Depositional environment

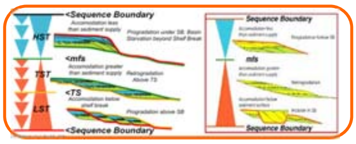


ANALYSIS

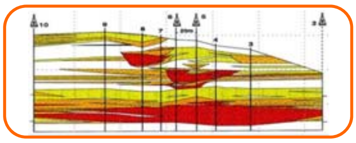
Structural analysis
- Structural style
- Faulting/folding phases



Sequence interpretation
- Identification of main surfaces (SB, MFS)



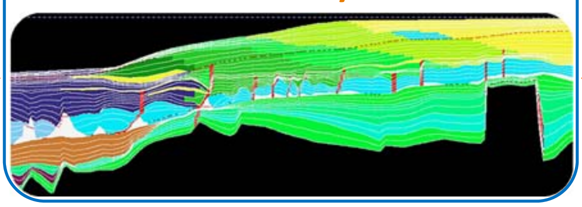
Identification of geobodies
- Facies distribution, correlations
- Depositional history



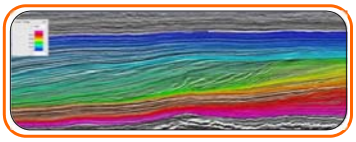
INTEGRATION

A priori geological knowledge
- Conceptual depositional model

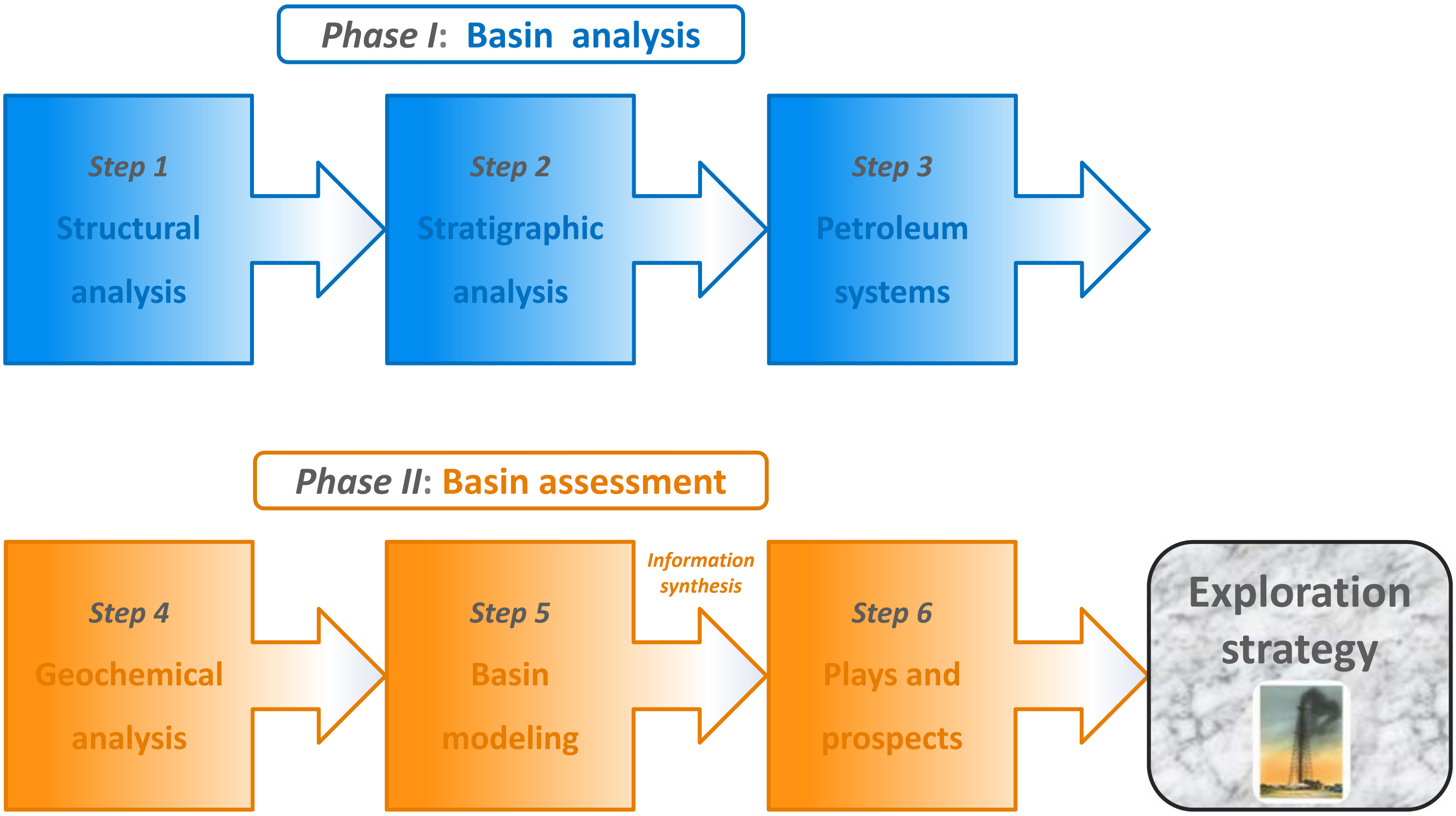
Petroleum system



Sequence stratigraphic framework
- Main surfaces, facies distribution



Basin exploration workflow



The four elements that make a valid prospect

- **A prospect is a buried geological object which is likely to contain HC (hydrocarbon, oil and/or gas) in sufficient quantities to allow an economically viable HC production project**

- **Need for the «petroleum tetralogy»:**
  - A source rock in order to generate HC
  - A reservoir rock with a capacity to collect HC
  - A seal rock above the reservoir with a full capacity to block HC moving upward
  - A trap in order to provide a wide-enough closed geometry

Basin analysis

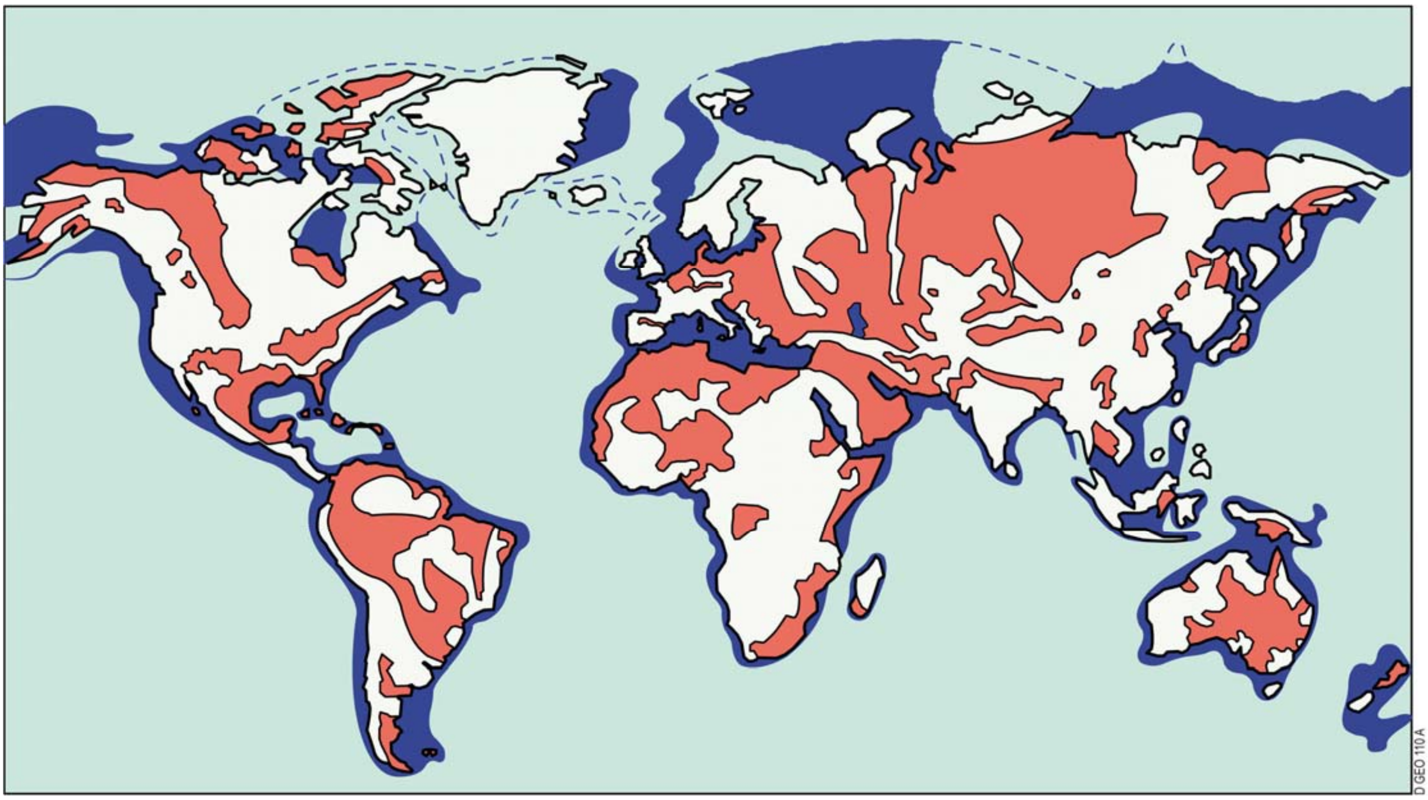
Basin analysis

I

- **Structural and thermal evolution during burial**
  - Earth structure - Geodynamics
  - Extensional context
  - Compressional context
  - Transform/shear context
  - Deformation styles

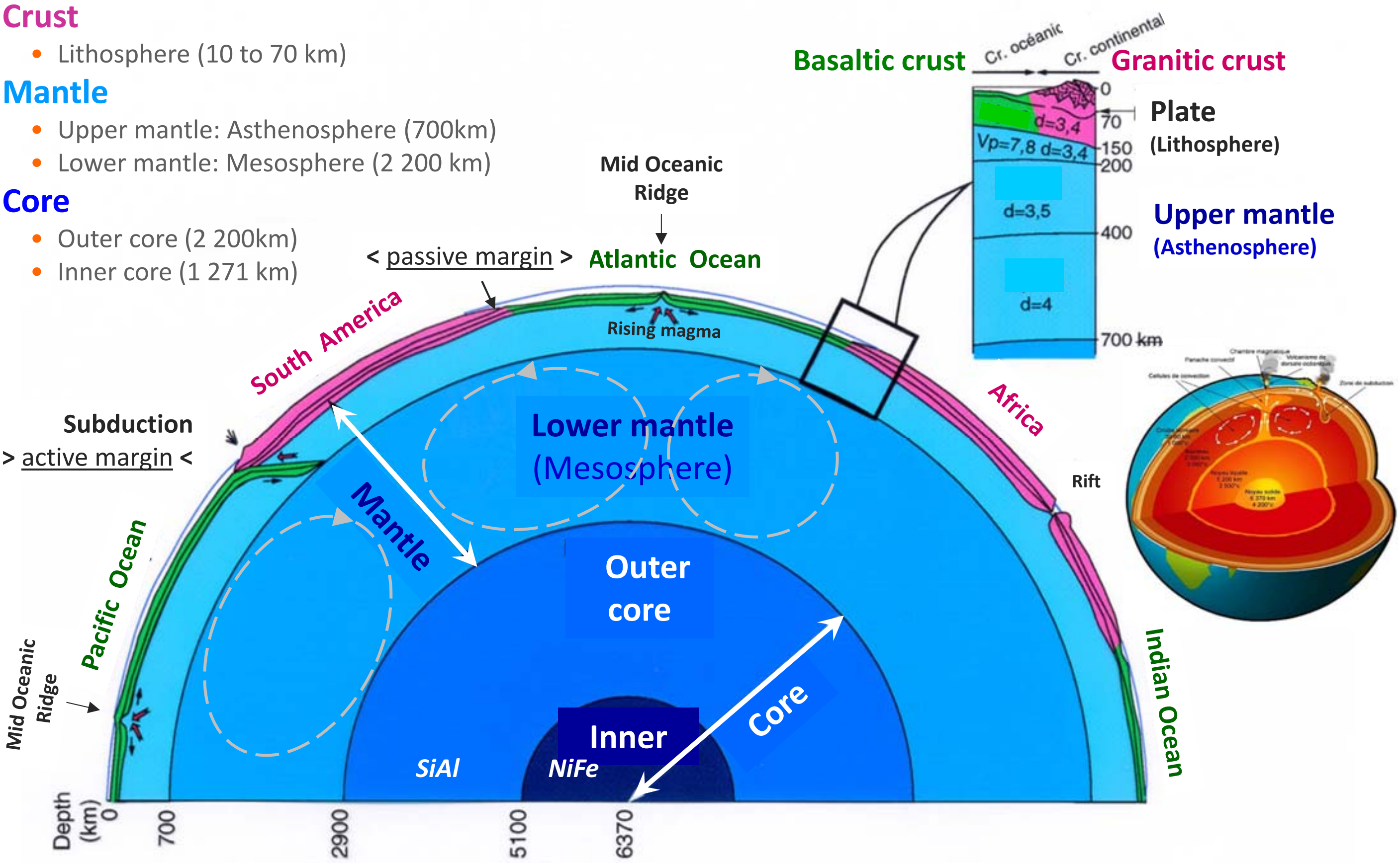
Map of sedimentary basins

***Onshore** and **Offshore** basins*



Structure of the Earth

- **Crust**
  - Lithosphere (10 to 70 km)
- **Mantle**
  - Upper mantle: Asthenosphere (700km)
  - Lower mantle: Mesosphere (2 200 km)
- **Core**
  - Outer core (2 200km)
  - Inner core (1 271 km)



Dynamics of the Earth: convection

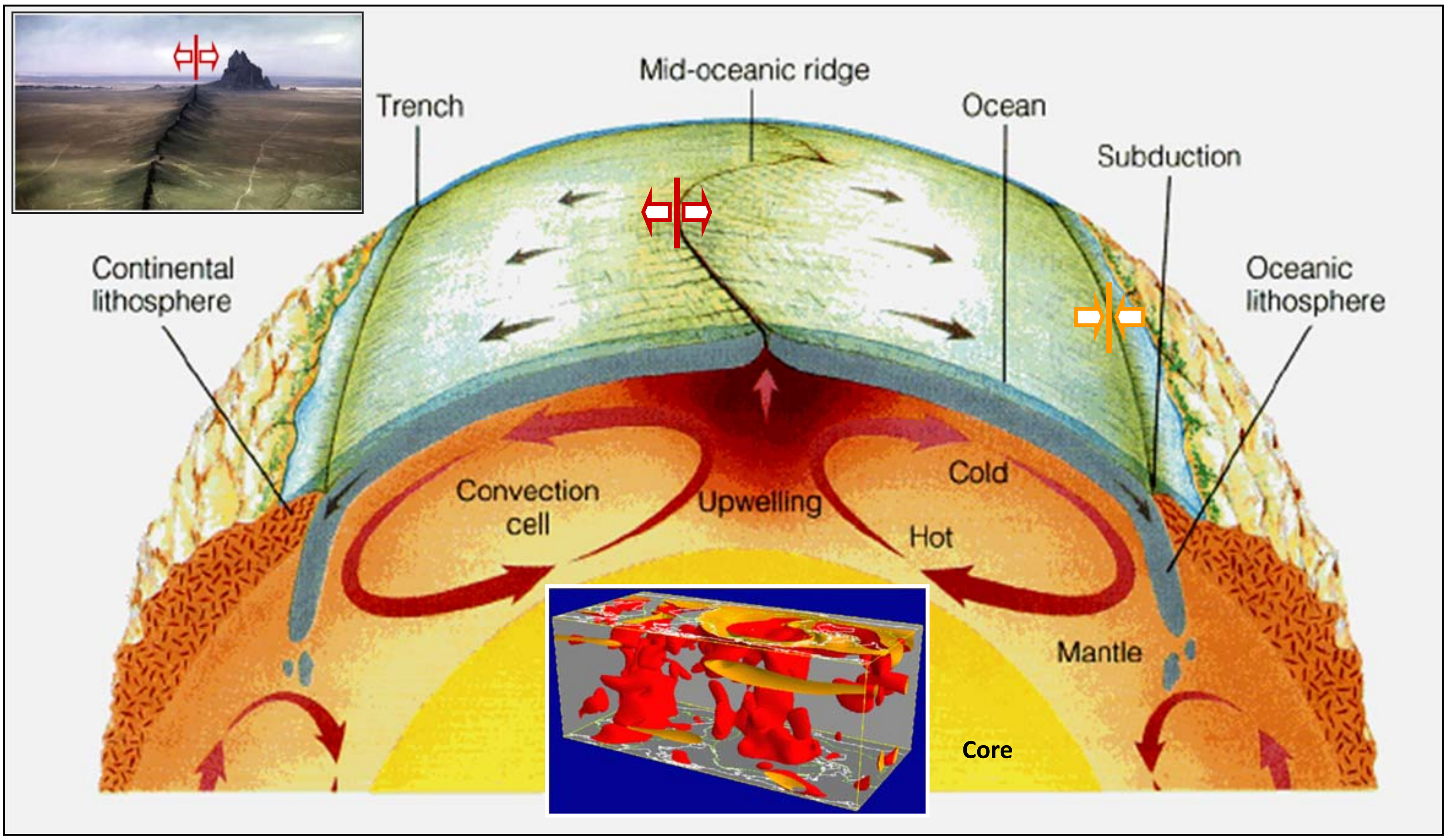
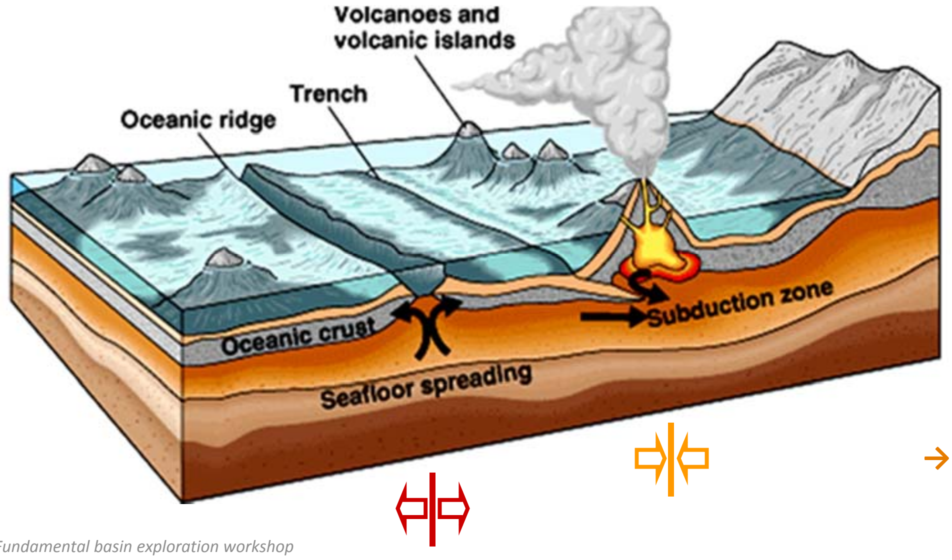
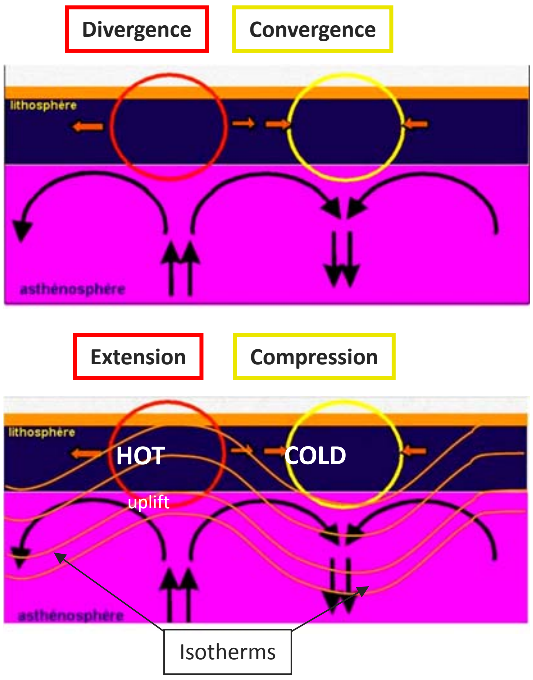


Plate boundaries: extension & compression

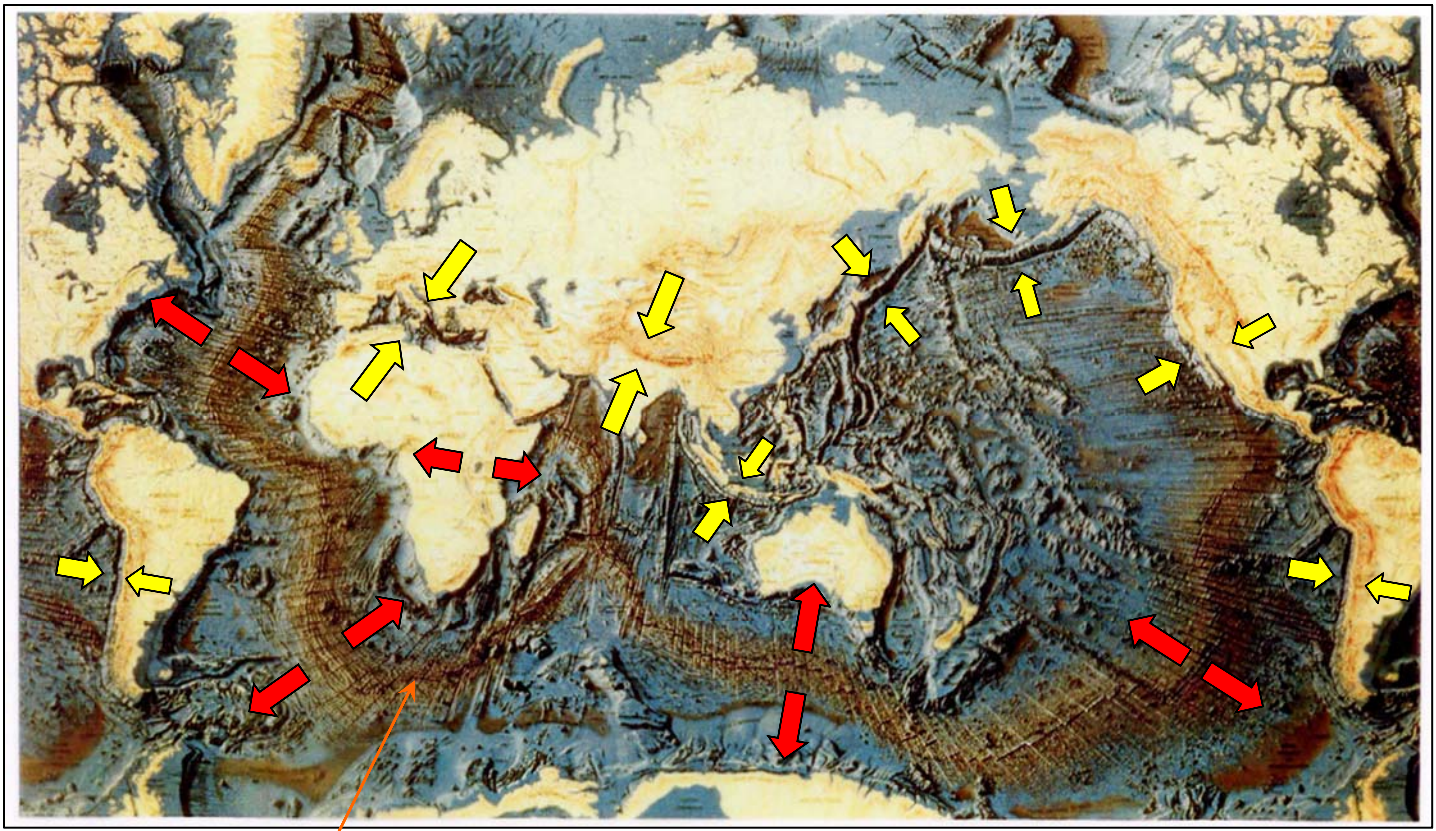
- **The lower limit of the lithosphere is an isotherm:**
  - below: hotter → plastic rock deformation (ductile)
  - above: colder → rigid rock deformation (brittle)
- **Upper mantle: rocks are hot**
  - viscous fluids behavior
- **Crust: rocks are cold**
  - rigidity allows stress transmission





→ **Driving mechanisms of plate tectonics and sedimentary basins formation**

Ocean bottom topography

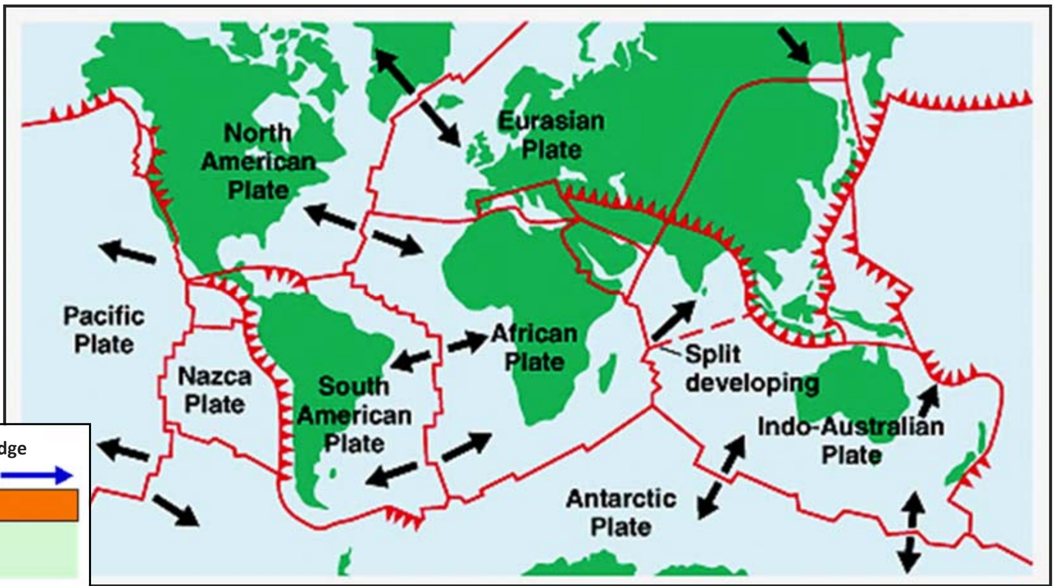


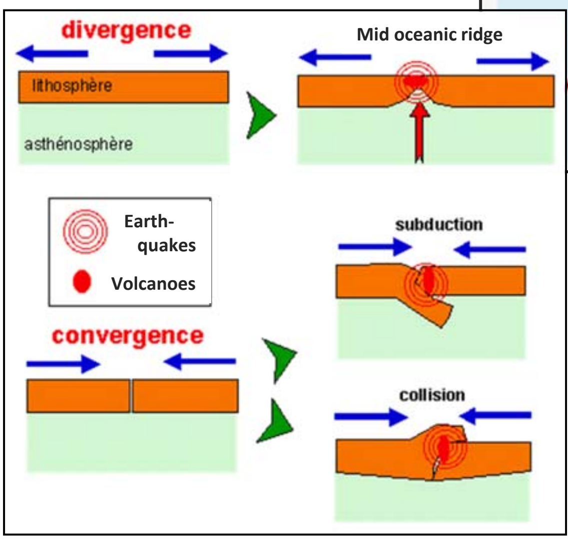
Mid oceanic ridges
(active subsea volcanic ranges)

Convergence
Divergence

Tethys Video

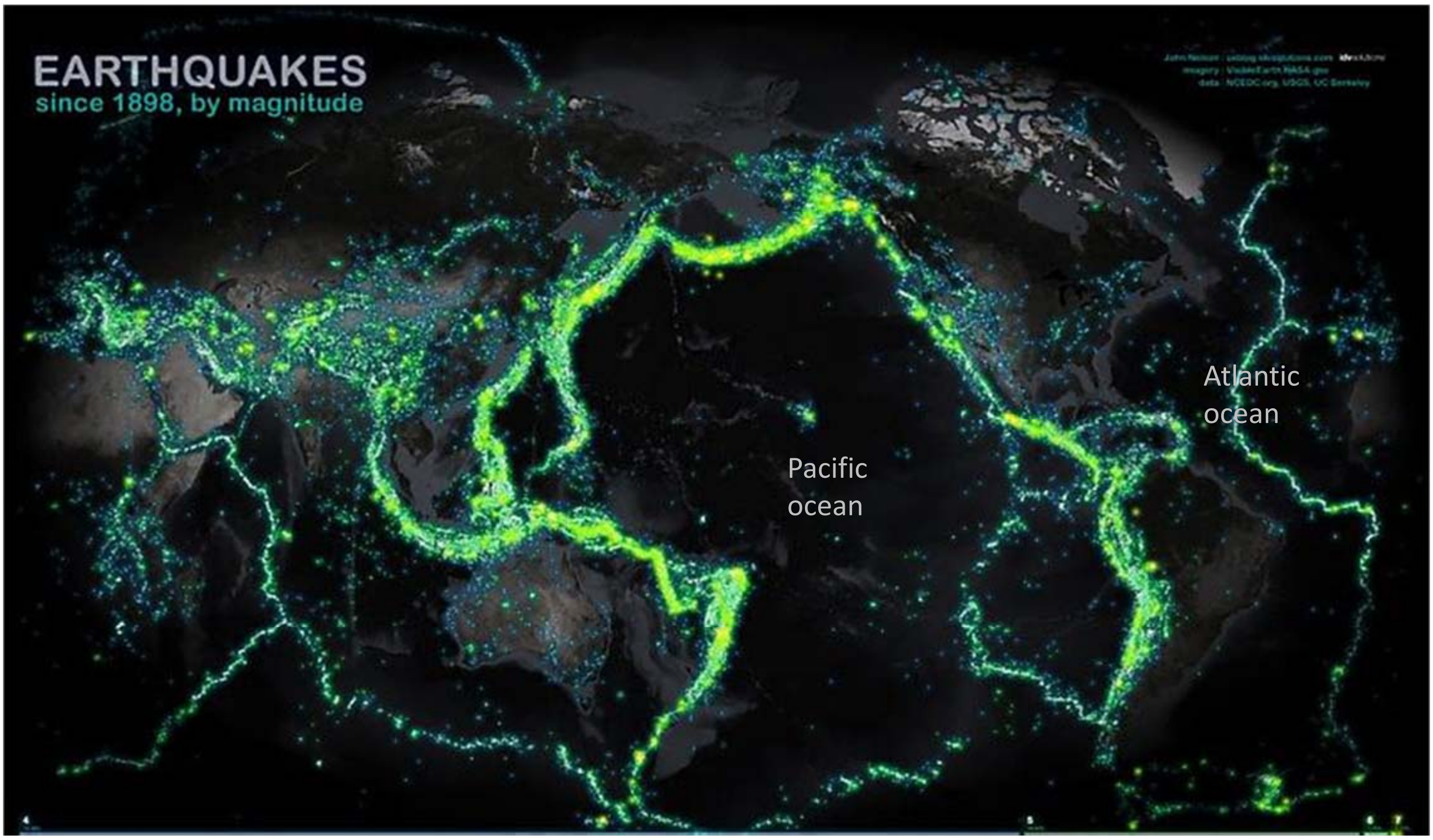
Tectonic plates





- **Lithospheric plate boundaries:**
  - **Divergent** (extensional: mid oceanic ridges)
  - **Convergent** (compressional: subduction, collision)
  - **Sliding/Shearing** (transform, strike-slip)

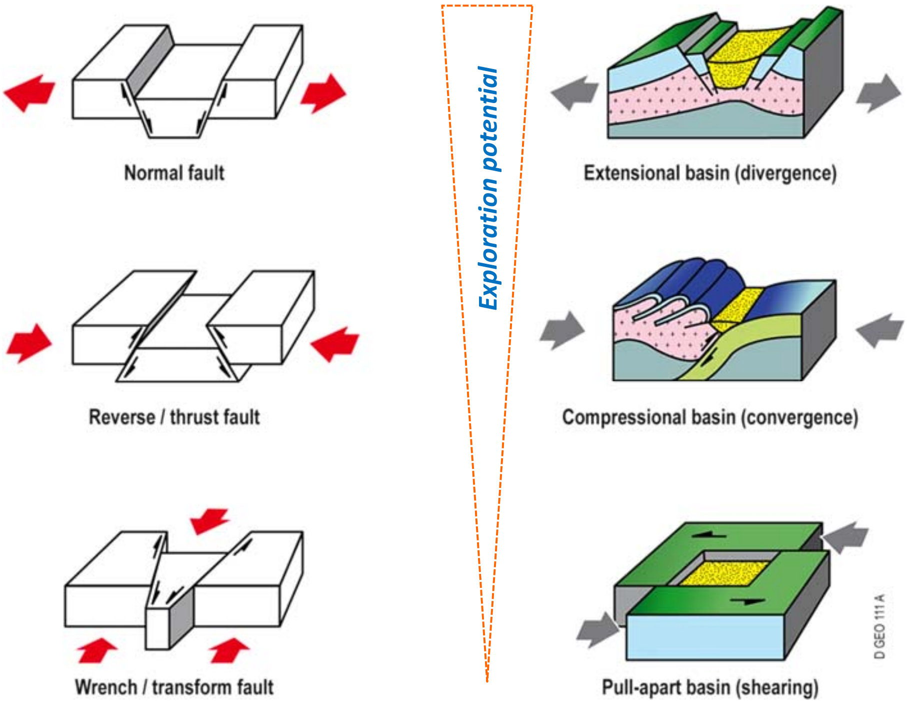
Earthquake activity



Seismicity along lithospheric plate boundaries

Types of margins and related basins

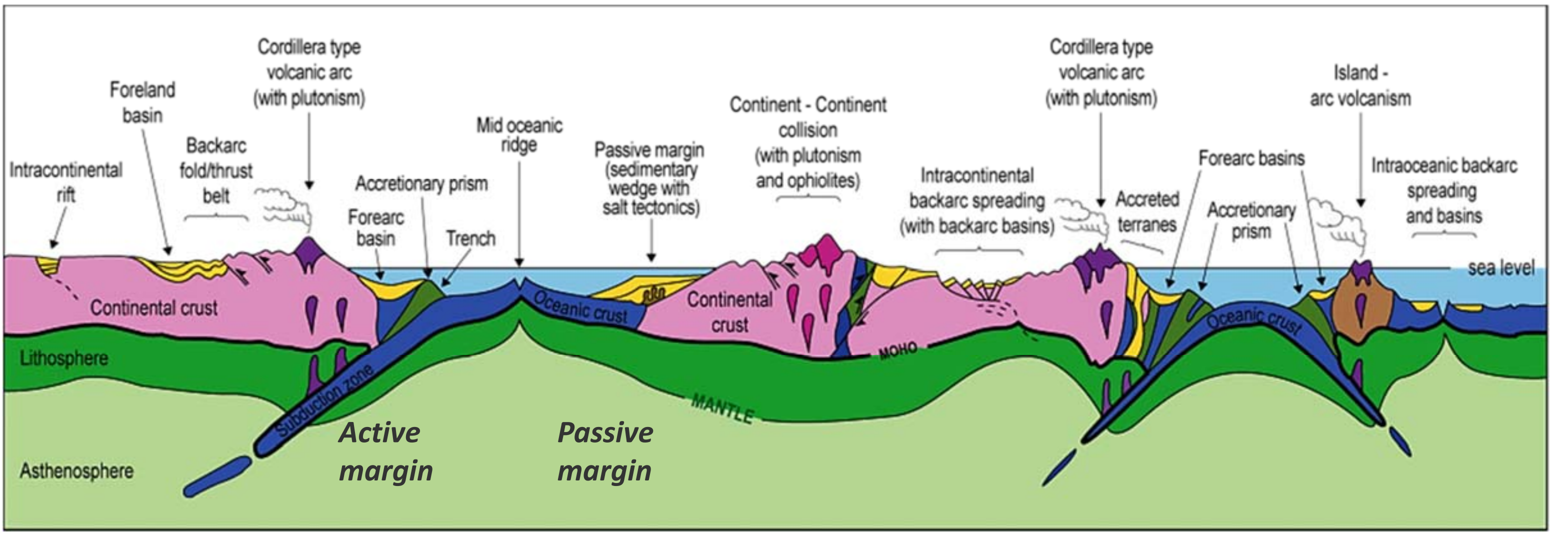
- **3 types of crustal stresses**
  - Extensional basins
  - Compressional basins
  - Shear basins
- **3 types of processes**
  - Purely thermal
  - Lithospheric thickness variation
  - Loading and unloading



Types of sedimentary basins and related deformations styles

Types of margins and related basins

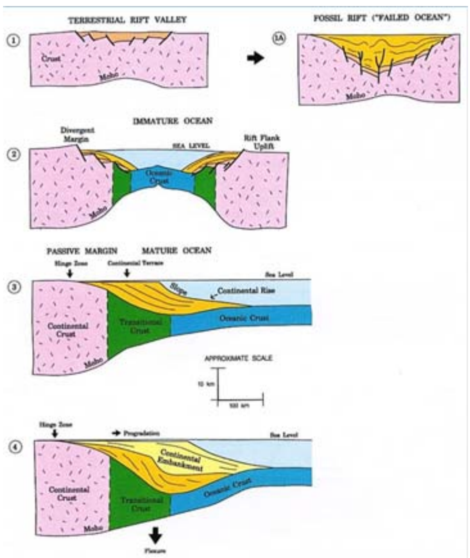
Sedimentary basins (*in yellow*)

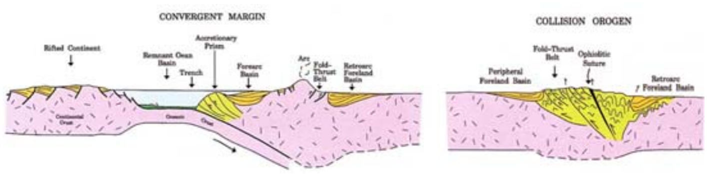


Sedimentary rocks cover 75% of the Earth's surface (continental crust) but only represent 5% of the crustal volume…

Types of sedimentary basins

- **Basins associated with plate divergence**
  Extensional basins
  - Rift, passive margin (plate divergence, ocean)
  - Intra-cratonic basin (intra-continental, intra-plate)
- **Basins associated with plate convergence**
  Compressional basins
  - Island arc-type margin (two oceanic plates)
  - Continental active margin (ocean / continent plates)
  - Inter-plate collision (two continental plates)
- **Basins associated with shearing** (sliding movement)
  Trans-tensional basins
  - Pull-apart basin (trans-tension: local distension in convergence)

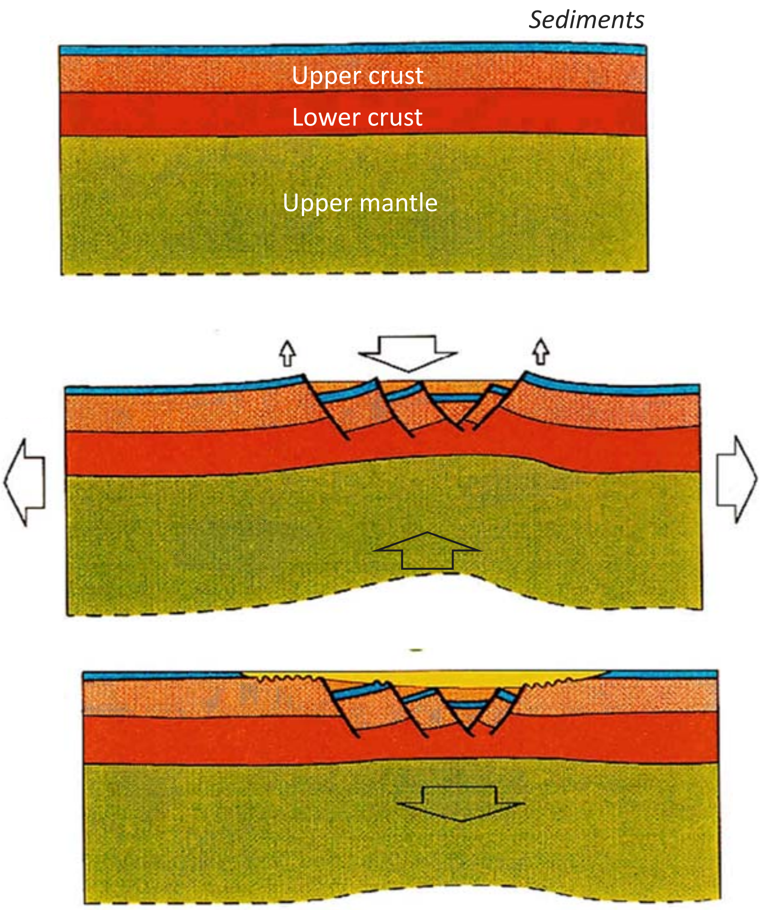




Basin analysis

- **Structural and thermal evolution during burial**
  - Earth structure
  - Extensional context
  - Compressional context
  - Transform/shear context
  - Deformation styles

Extensional context: rift basins



- Rifts are areas of crustal extension and thinned continental crust. Rifting areas are characterized by lithospheric stretching, high heat flow and volcanic activity caused by a thermal anomaly at depth (convection)

- Rift zones:
  - Heat flow of 90 to 110mW.m^{-2}
  - High levels of earthquake activity and a dome-shaped Moho
  - Normal faults network

- Examples: Red Sea and Ethiopia / Djibouti

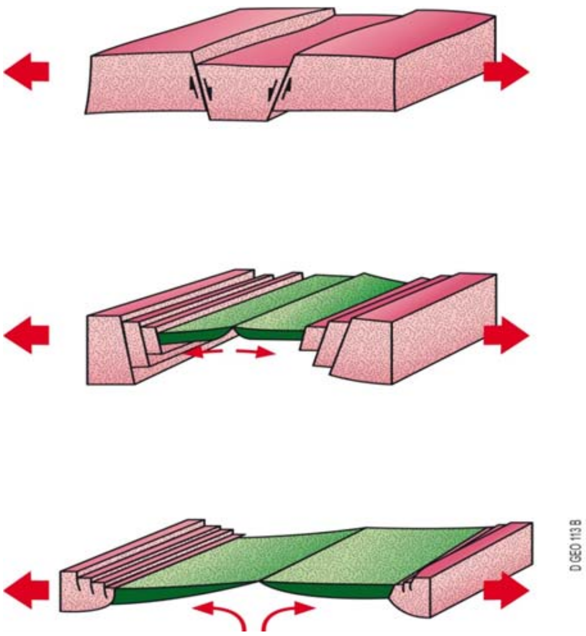
Basins associated with plate divergence

Rift evolution

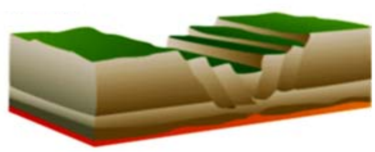
Graben
(East Africa)

Sea
(Red sea)

Ocean
(Atlantic)



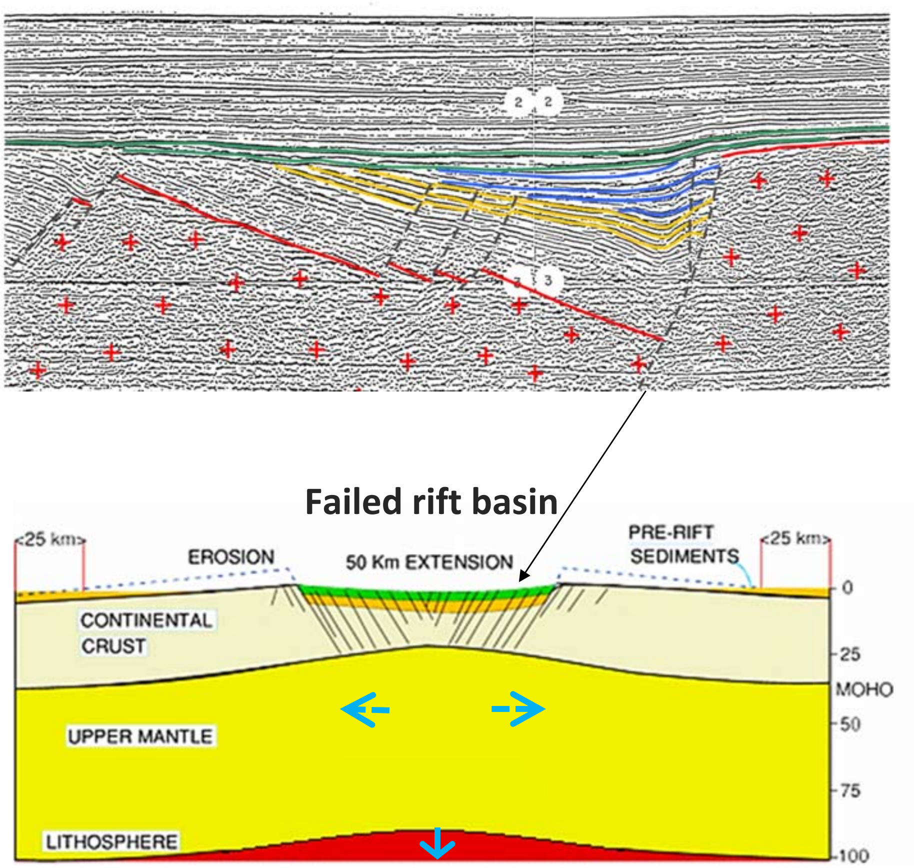
Lithospheric stretching (extension: faulting)
Intracratonic rift valley
Continental environment (lakes)



Lithospheric breaking
Plate splitting
Shallow marine environment

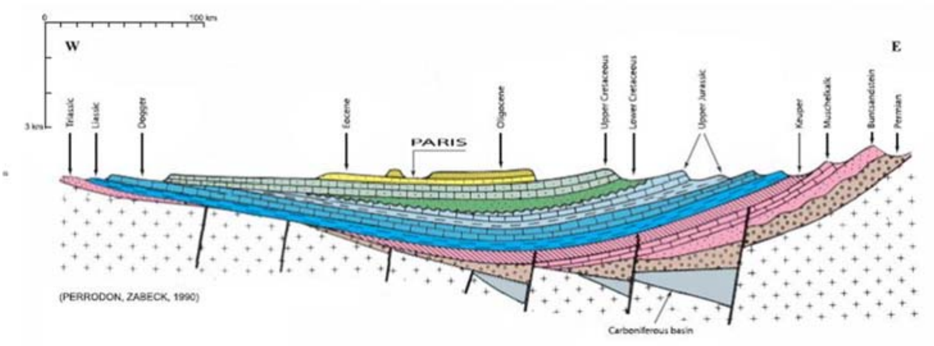
Continental drift (no more stretching: passive margins)
Seafloor spreading
Open marine environment

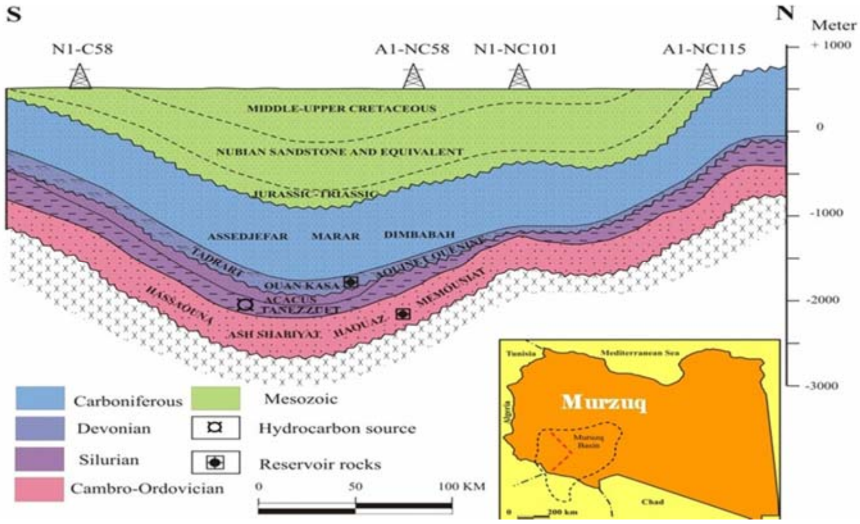
Failed rift basins



- **Aborted rifting mechanisms and lithospheric stretching due to a gradually diminishing thermal anomaly (cooling)**
- **Failed rift zones:**
  - Heat flow of 80 to 90mW.m^{-2}
  - A reducing of seismic and volcanic activity
  - A normal faults network covered a disconformity
- **Examples: North Sea and in Rhine-Bresse (France)**

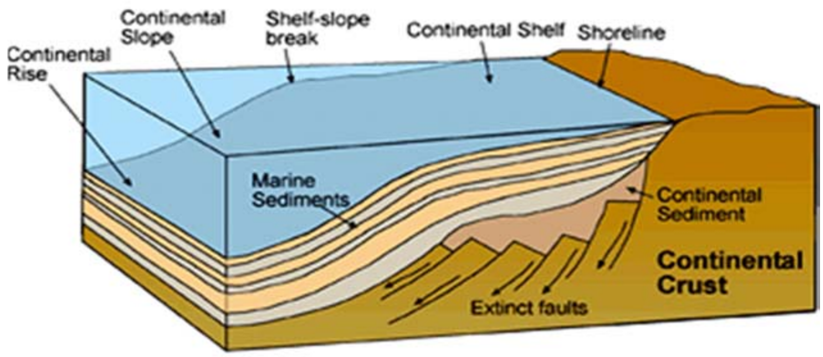
Intra-cratonic basins

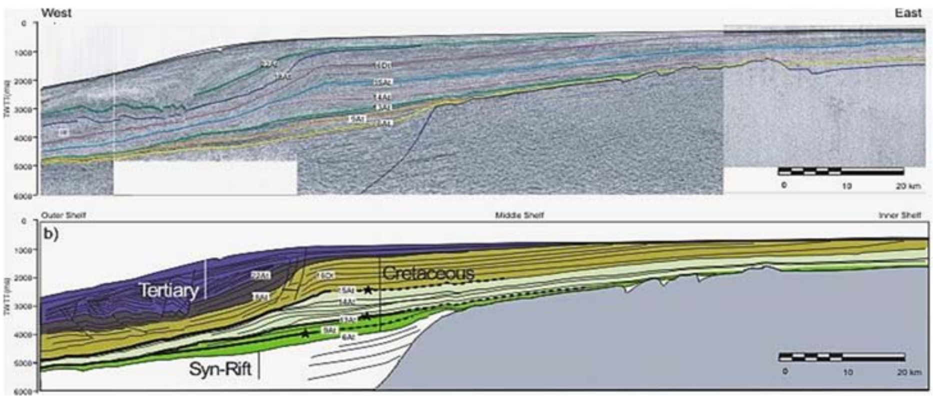




- Intra-cratonic basins are large depressions in continental crust. They have a slow and homogeneous sedimentary filling
- Intra-cratonic basins:
  - Have a heat flow near-normal (60 to 80mW.m^{-2})
  - Are seismically inactive
  - Have sediment overlain on faults and syn-rift sediments
- Examples: Paris basin and Middle-East

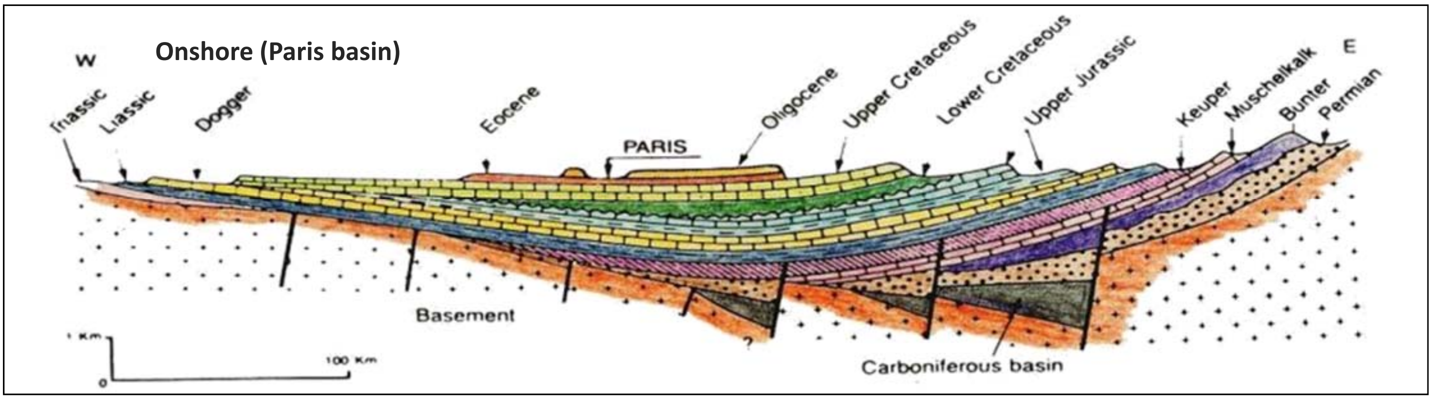
Passive margins

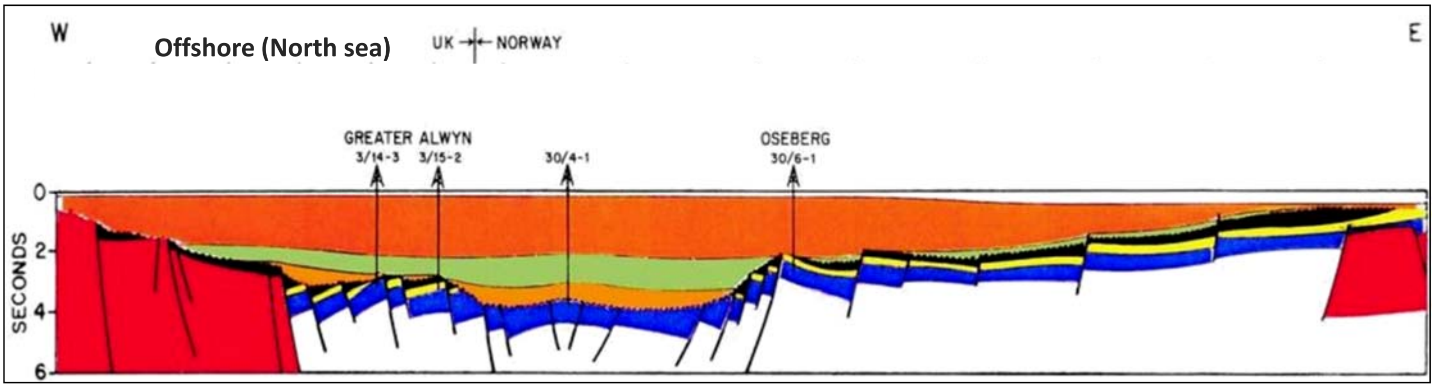




- Beginning of rifting mechanisms and stop of lithospheric stretching caused by a reducing and cooling of the thermal anomaly
- Passive margin zones:
  - Have a heat flow near-normal (60 to 80mW.m^{-2})
  - Are seismically inactive
  - Have sediment overlain on faults and syn-rift sediments
- Examples: West Africa and Eastern South America

Extensional basins examples



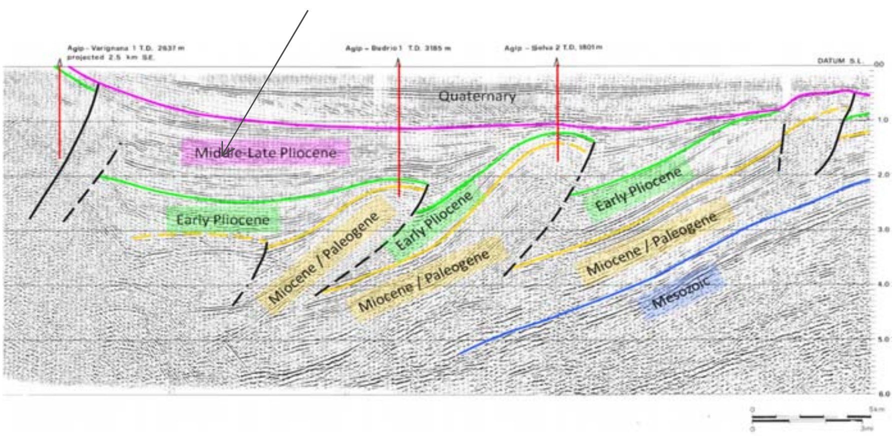


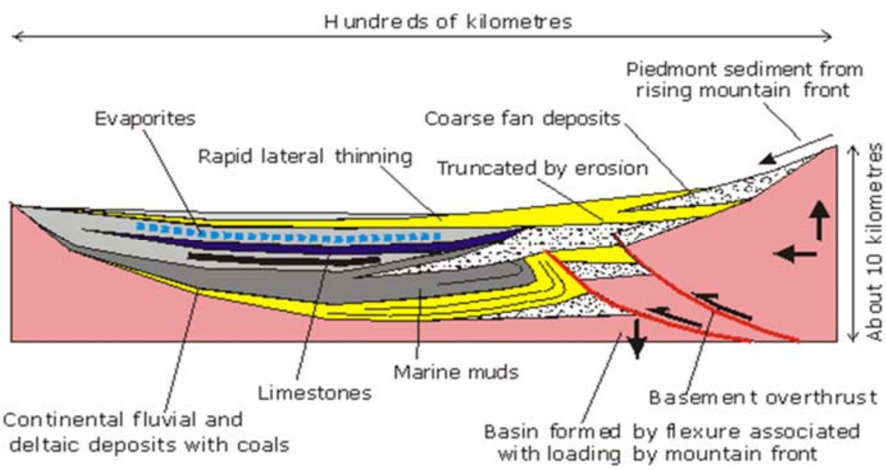
▶ **Structural and thermal evolution during burial**

- Earth structure
- Extensional context
- Compressional context
- Transform/shear context
- Deformation styles

Foreland basins

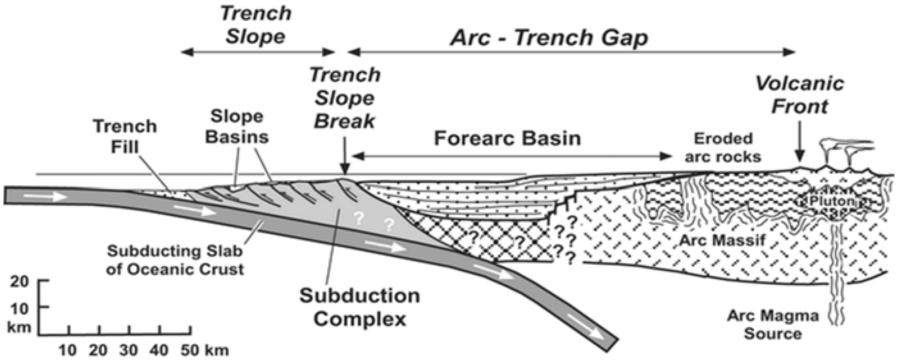
Foreland basin

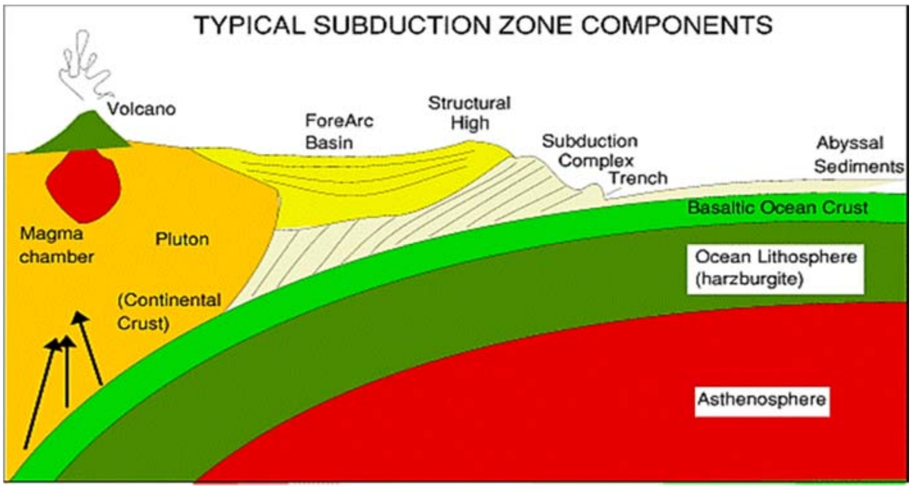




- ▶ Foreland basins result from the downward flexing of the lithosphere in response to the weight of an adjacent mountain belt (although several geodynamic processes combine to control their evolution)
- ▶ Foreland basins:
  - Have a near-normal heat flow (60 to 80mW.m^{-2})
  - Are seismically active
- ▶ Examples : Alps, Himalayan and Appalachian ranges

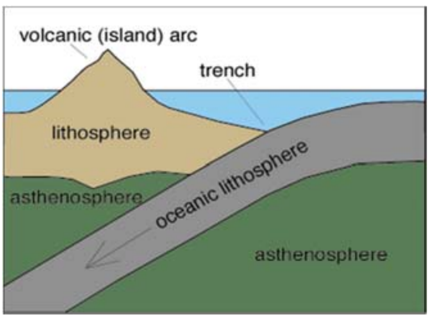
Forearc basins

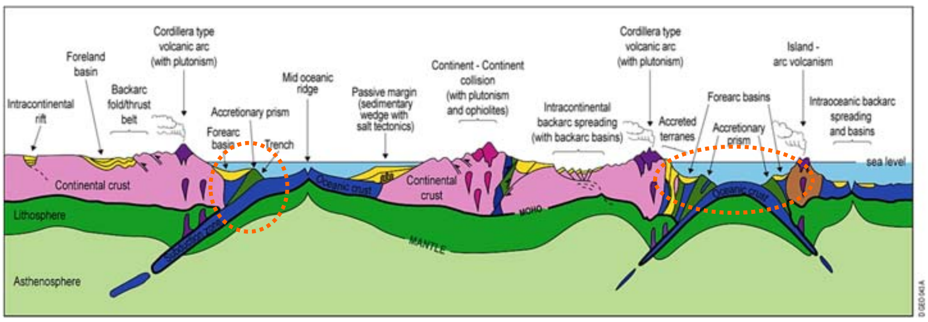




- This basin is located between the volcanic arc and the subduction complex
- Fore-arc basins:
  - Are seismically very active
- Examples: Andes, Java and Sumatra islands

Oceanic trench basin

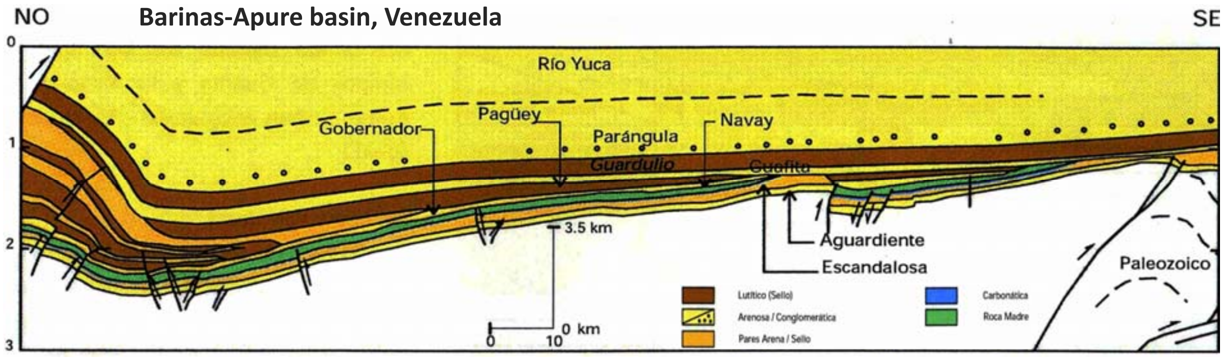




- Oceanic trenches are the deepest parts of the ocean floor where the lithosphere is subducted under another plate
- Oceanic trenches:
  - Show a high seismic activity
  - Have an associated accretionary prism
- Examples: western South America and eastern Japan

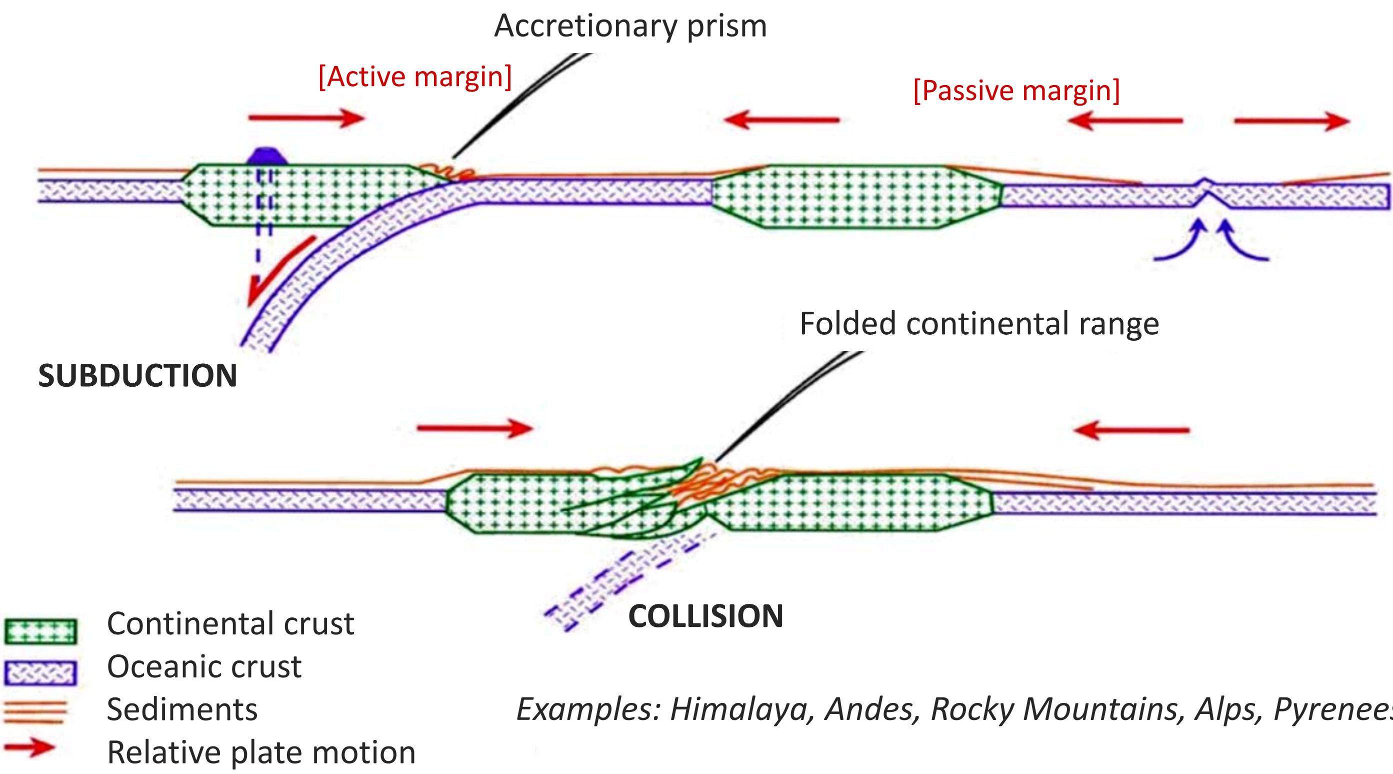
Compressional basins examples (foreland)

Barinas-Apure basin, Venezuela



Basins associated with plate convergence

Process of mountain range creation: orogenesis



Examples: Himalaya, Andes, Rocky Mountains, Alps, Pyrenees, …

Distribution of margins and related basins

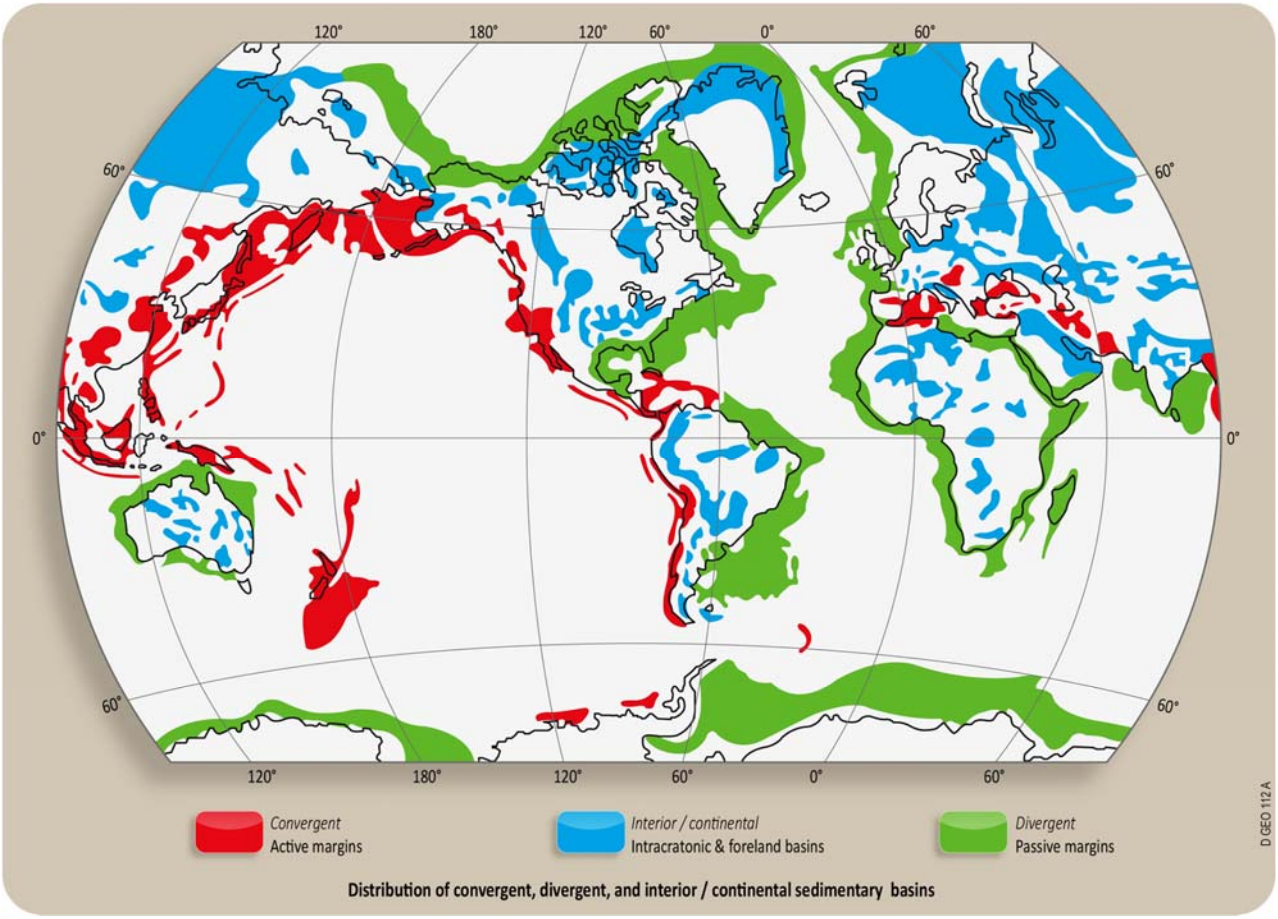
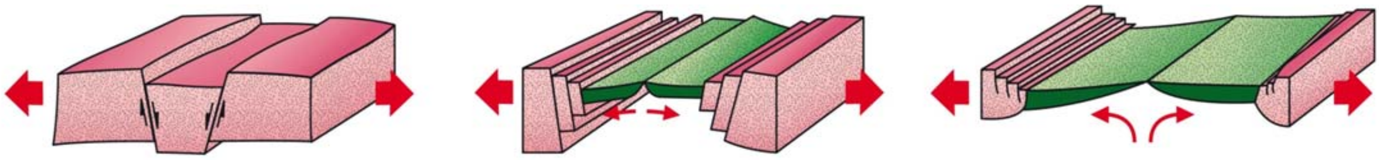


Plate tectonics summary: Wilson's cycle

Graben **Sea** **Ocean**

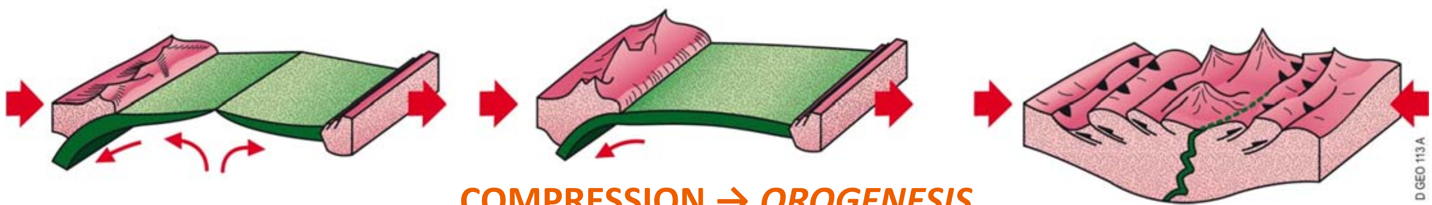


EXTENSION → *RIFTING*

Sea floor spreading rate controls sea level changes!

From graben to mountain: a cyclical history of the ocean floor…

Subduction **Subduction** **Collision**



COMPRESSION → *OROGENESIS*

Ophiolite scar

Oldest oceanic crust: 240 My → older oceans were incorporated in previous collisions

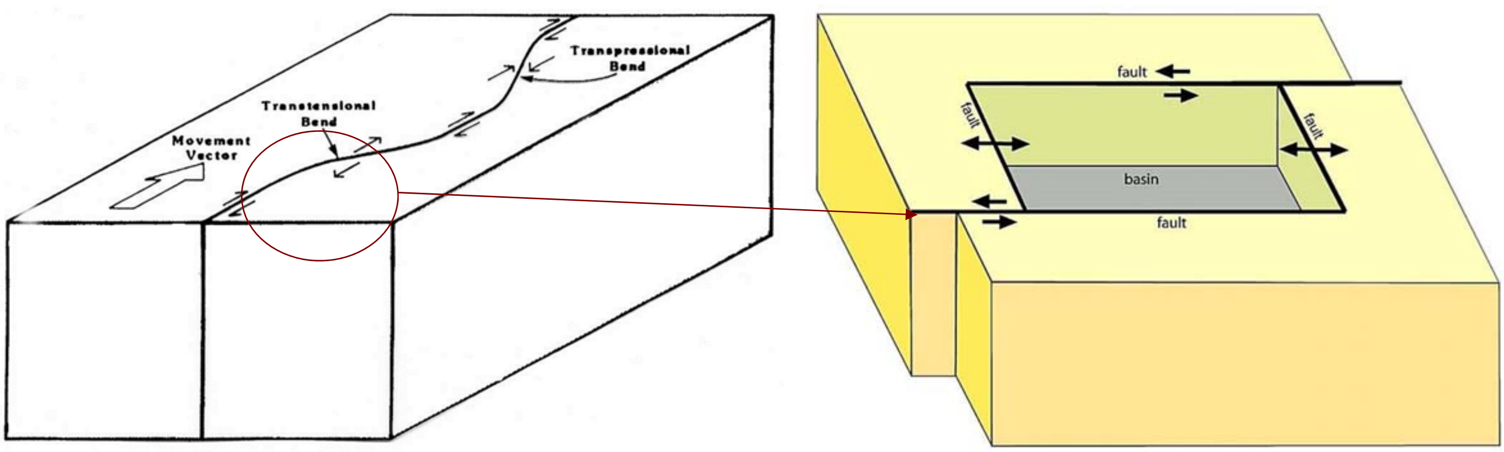
Structural and thermal evolution during burial

- Earth structure
- Extensional context
- Compressional context
- Transform/shear context
- Deformation styles

Basins associated with shearing / strike-slip

Sliding/Shearing boundary between two plates (or within a plate):

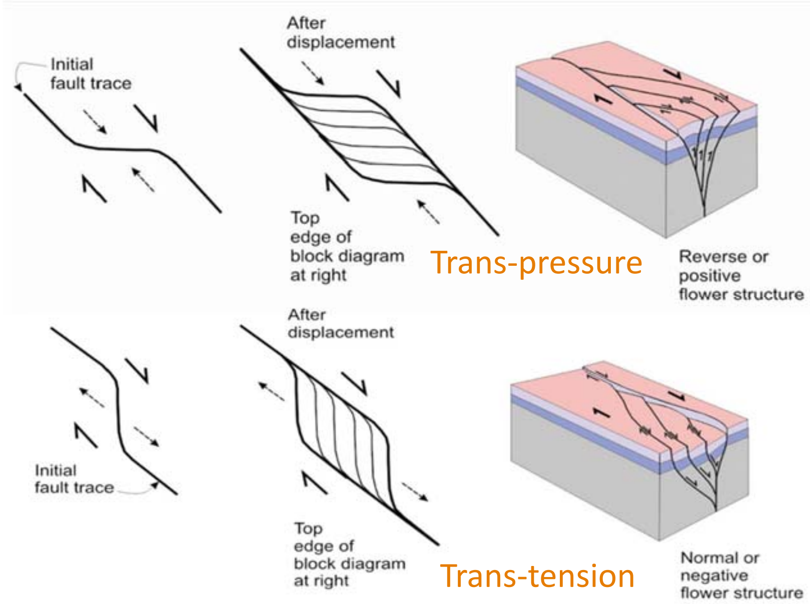
- **Pull-apart basin** between two strike-slip faults or along a bend (extremely fast subsidence)

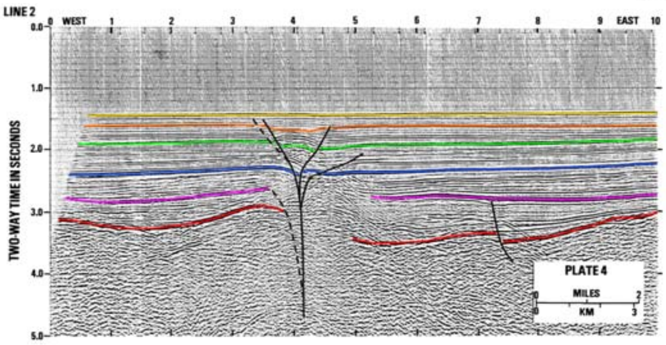


Local shear deformation style depends on fault geometry:

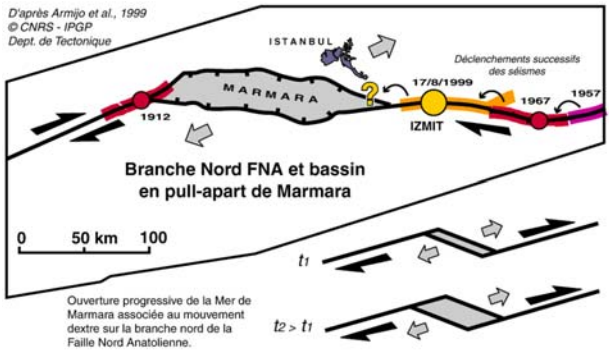
- transtensional: local extension
- transpressional: local compression

Strike-slip (pull-apart) basins





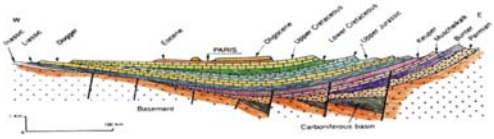
- Strike-slip basins are due to transform fault movements
- If the blocks move away from their initial position, it is a trans-tensional movement so there are normal faults associated to the flower structure
- Symmetrically, trans-pressional movement induces reverse faults



Main features and examples – 1/2

Basins in intracontinental areas:

- **Intra-cratonic basins (large depressions in continental crust)**
  - weak subsidence
  - light structural deformation
  - slow, homogeneous sedimentary filling

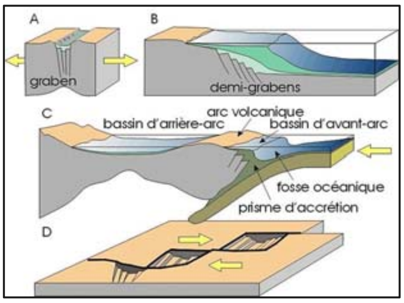


Examples : Middle-East, Sahara (Algeria, Libya), Paris basin, Sverdrup basin (Canada).

- **Rift-type basins (intracontinental)**
  - swelling, then collapsing of continental crust
  - strong subsidence in the central area (plate splitting)
  - progressive but fast sedimentary filling

Examples : Viking Graben (North Sea), Suez Gulf.

Basins on plate boundaries:



Passive margins basins (continental)

- continent-ocean transition zone
- symmetrical basins
- Two major phases of evolution: rift and post-rift
  - rift : vertical displacement, normal faults, various sedimentation modes
  - post-rift : generalized subsidence, very important sedimentation rate

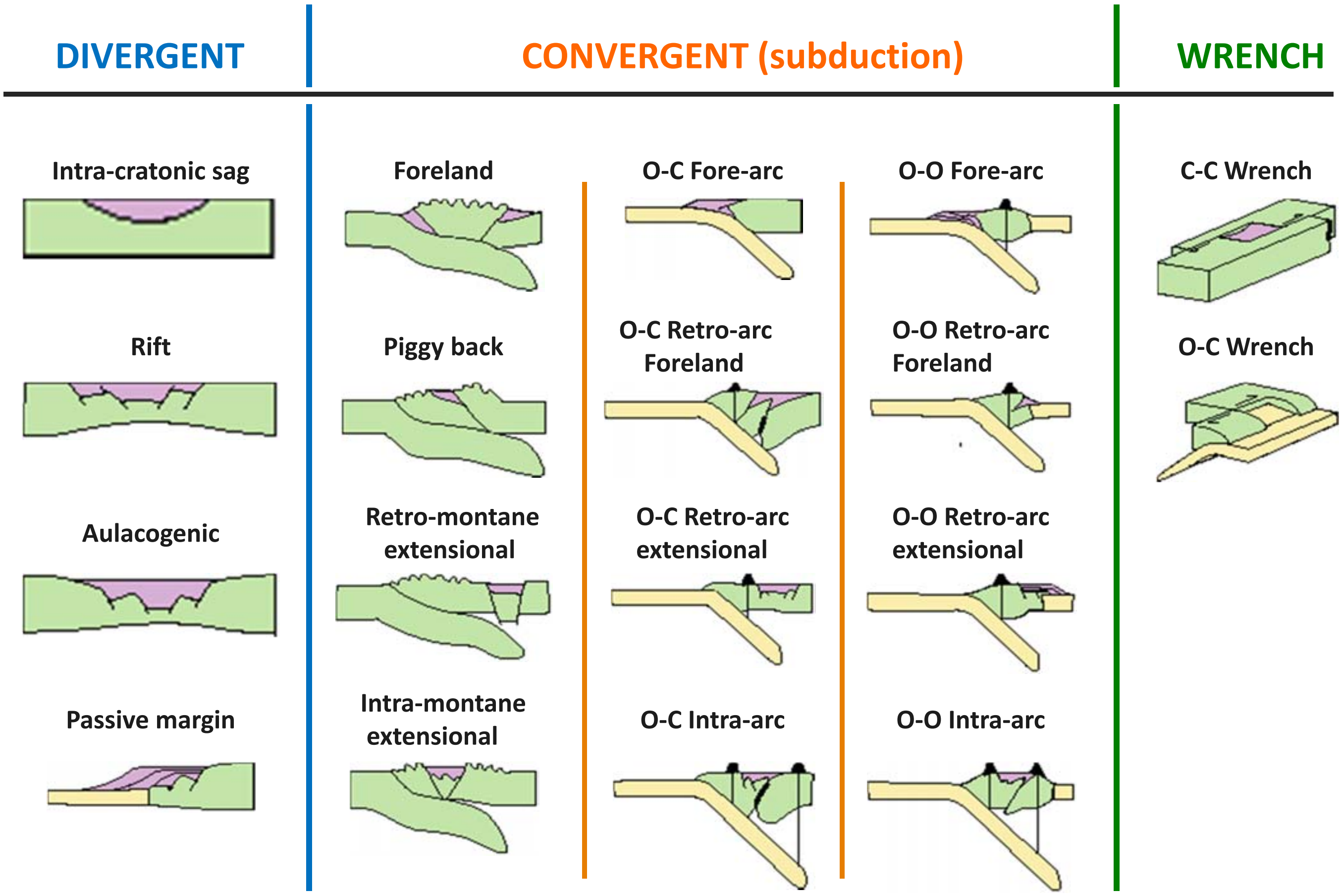
Examples : Gulf of Guiney (Zaire river delta [Gabon, Congo, Angola], Niger river delta [Nigeria, Cameroon]), Brazil (Sergipe, Alagoas, Campos), Gulf of Mexico.

Active margins basins (subduction zones)

- located on plate collision zones
- asymmetrical basins
- particularly unstable and often mobile zones (high seismicity)
- varied structural complexity

Examples : California, Western South-America, Aquitaine, Indonesia.

Classification of sedimentary basins



Tectonic regimes and related types of sedimentary basins

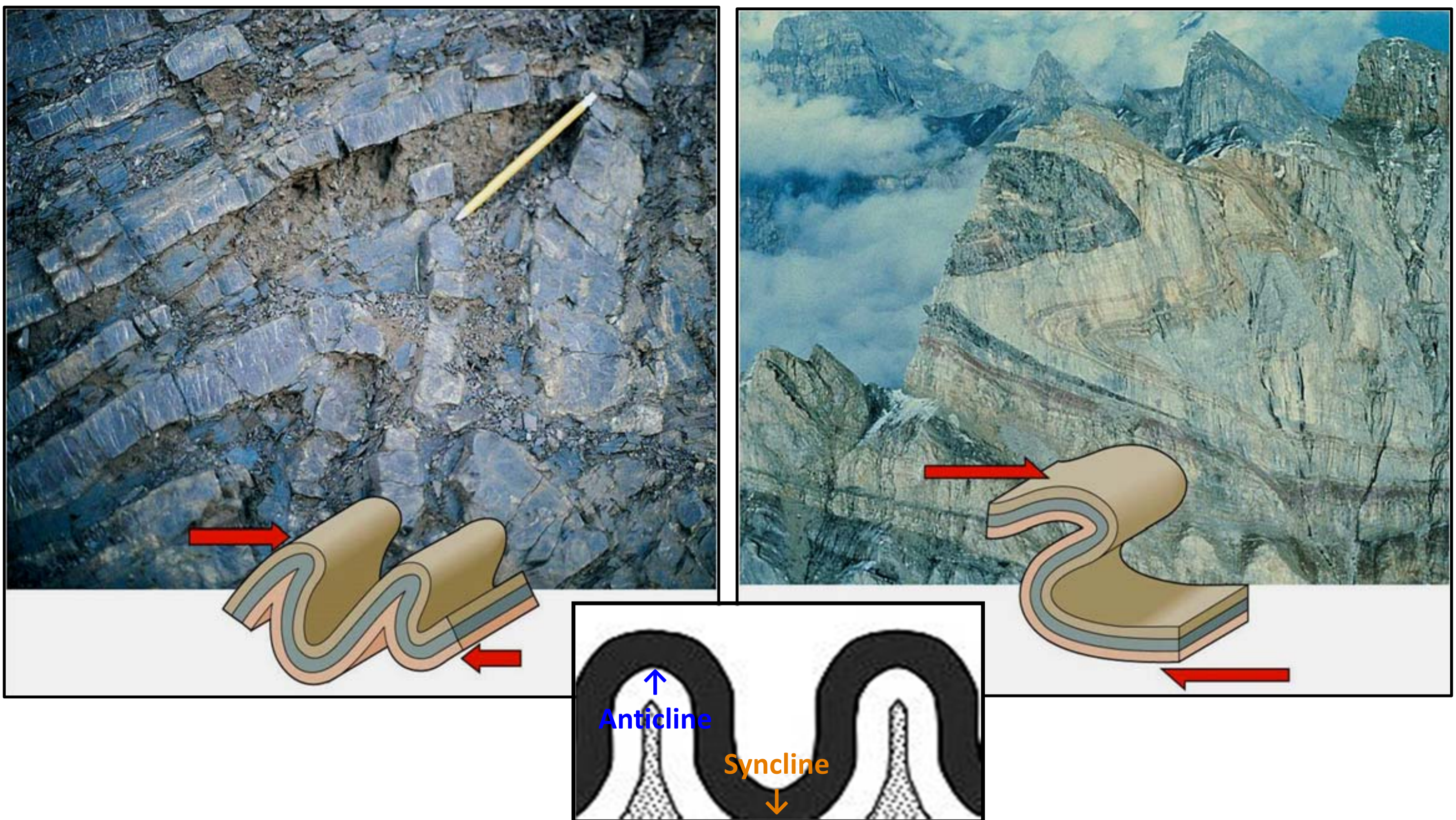
Basin analysis

▶ Structural and thermal evolution during burial

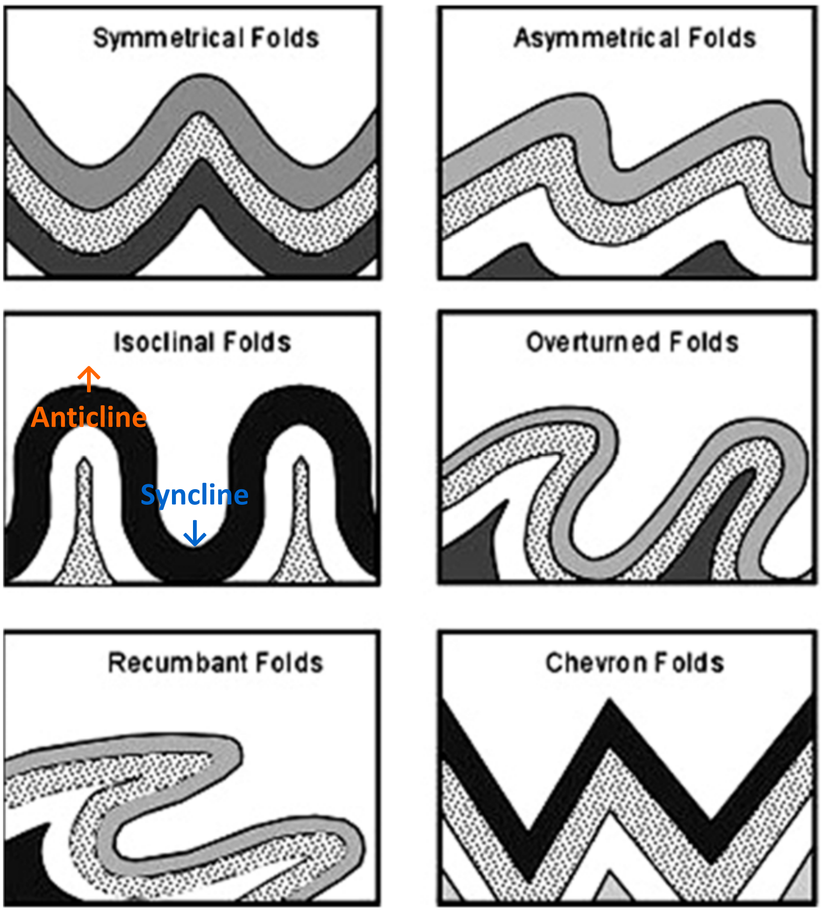
- Earth structure
- Extensional context
- Compressional context
- Transform/shear context
- Deformation styles (ductile vs brittle)

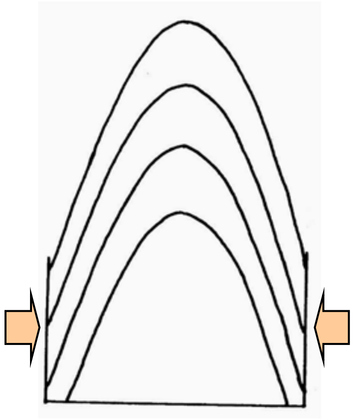
Folds: ductile deformation

Scale: from mm to km…

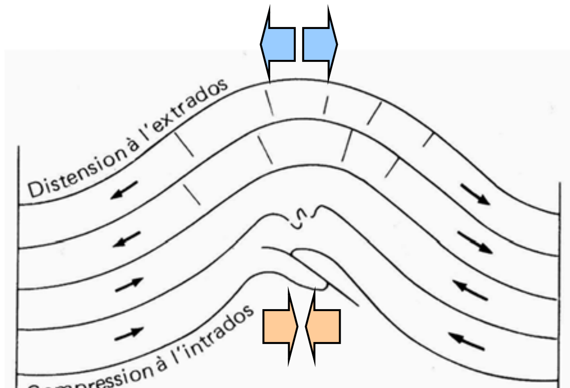


Types of folds



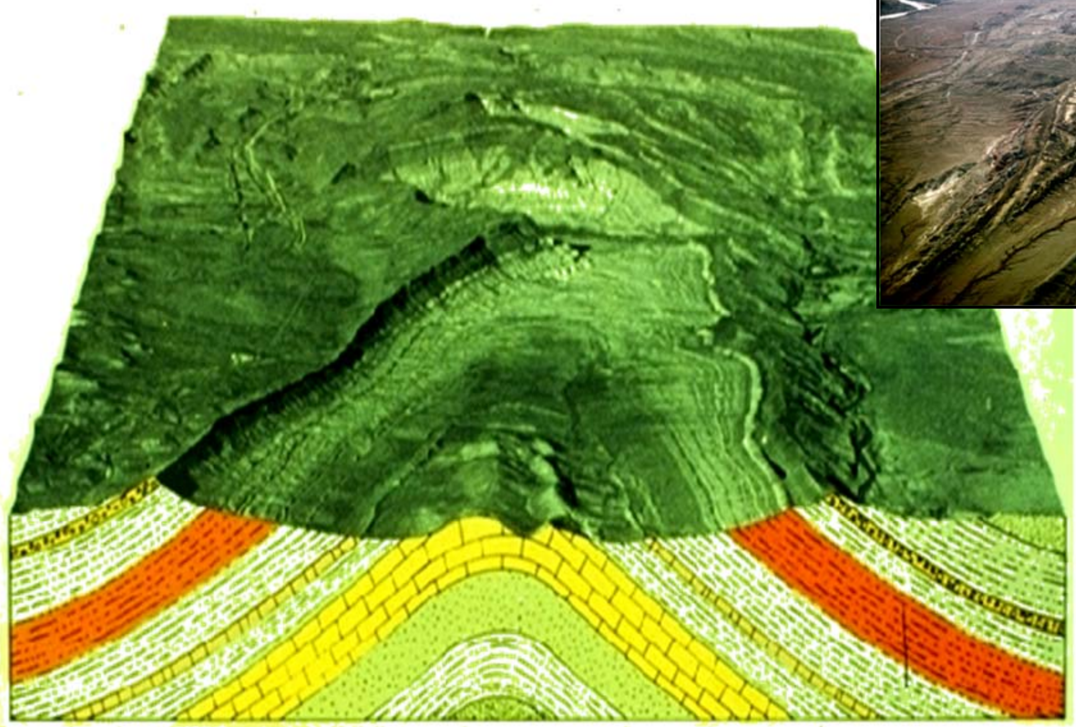


Similar fold



Concentric fold

Eroded folds

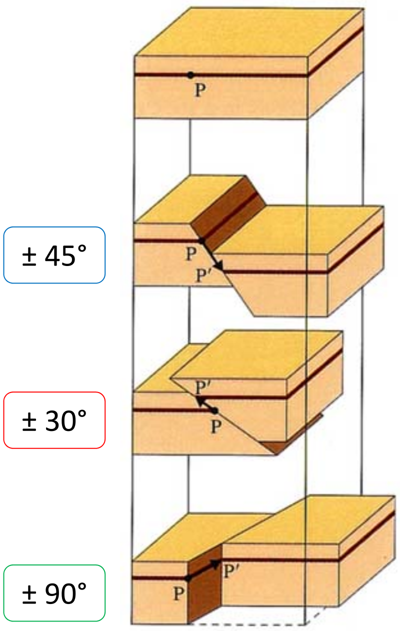


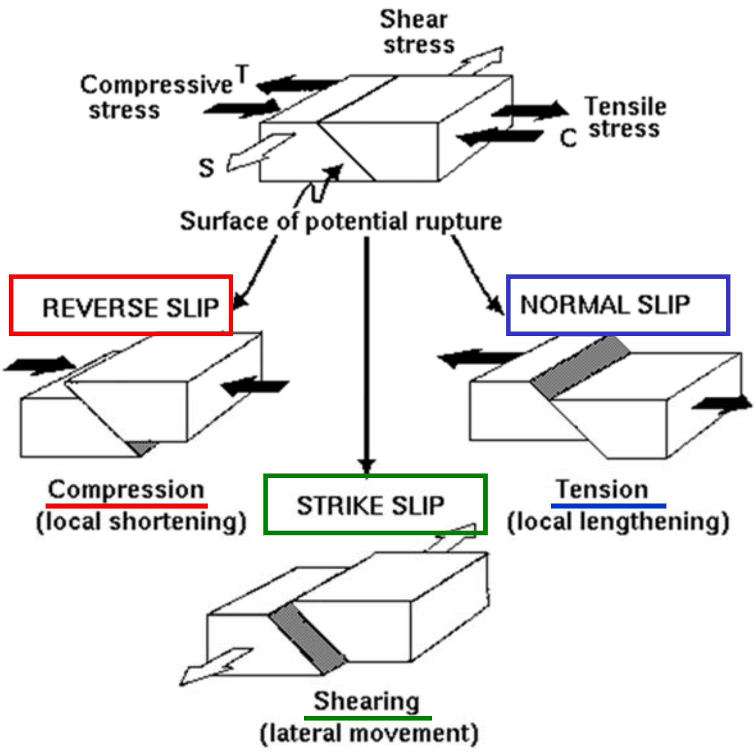
Anticline

Anticline ↑ and syncline ↓

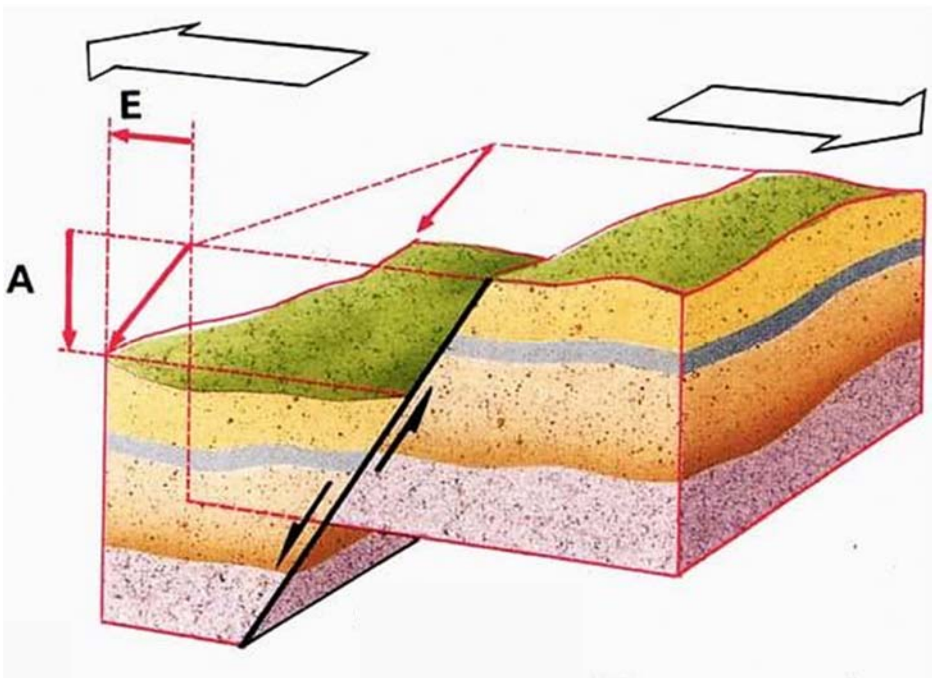
Faults: brittle deformation

- 3 types of faults
  - **Normal** (extension)
  - **Reverse** (compression)
  - **Strike-slip** (shear)

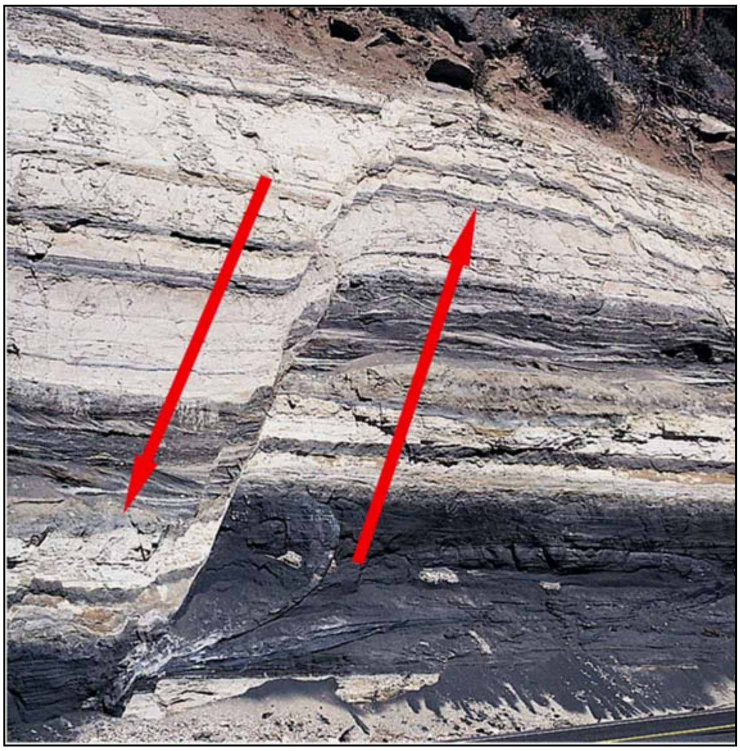




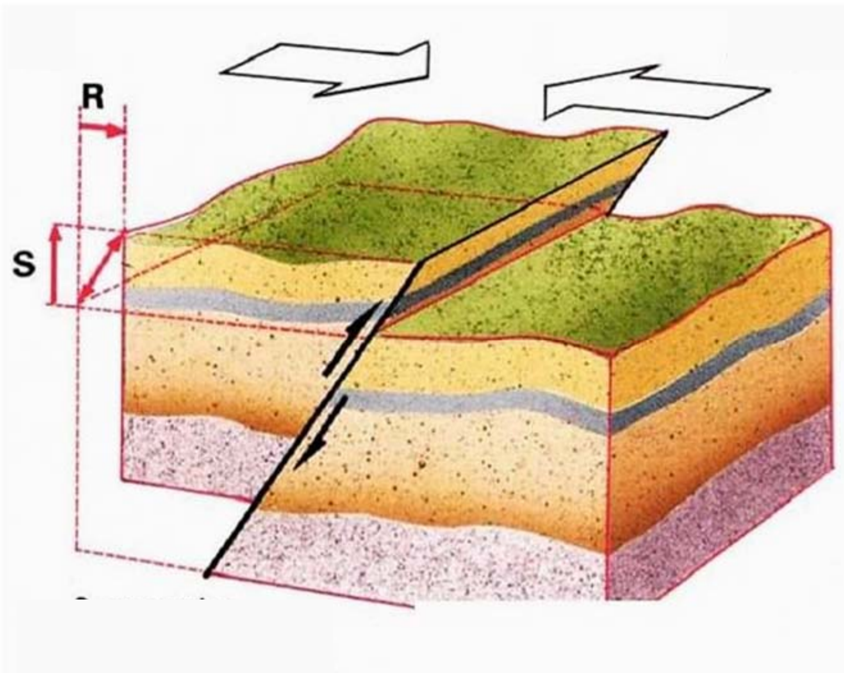
Extension: normal fault



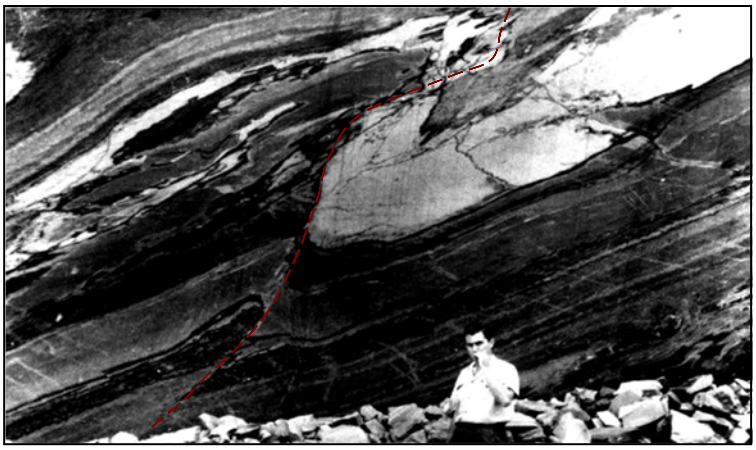
Extension: normal fault



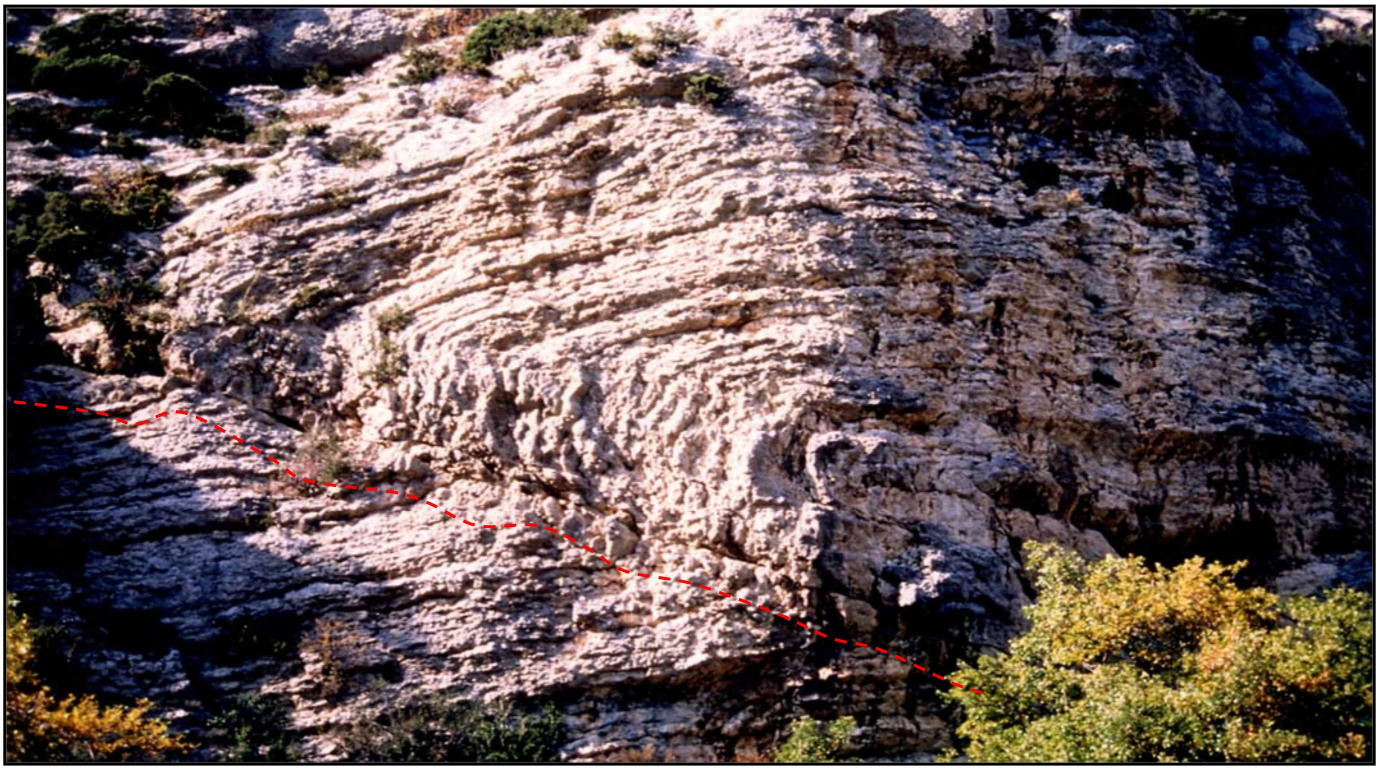
Compression: reverse fault



Compression: reverse fault

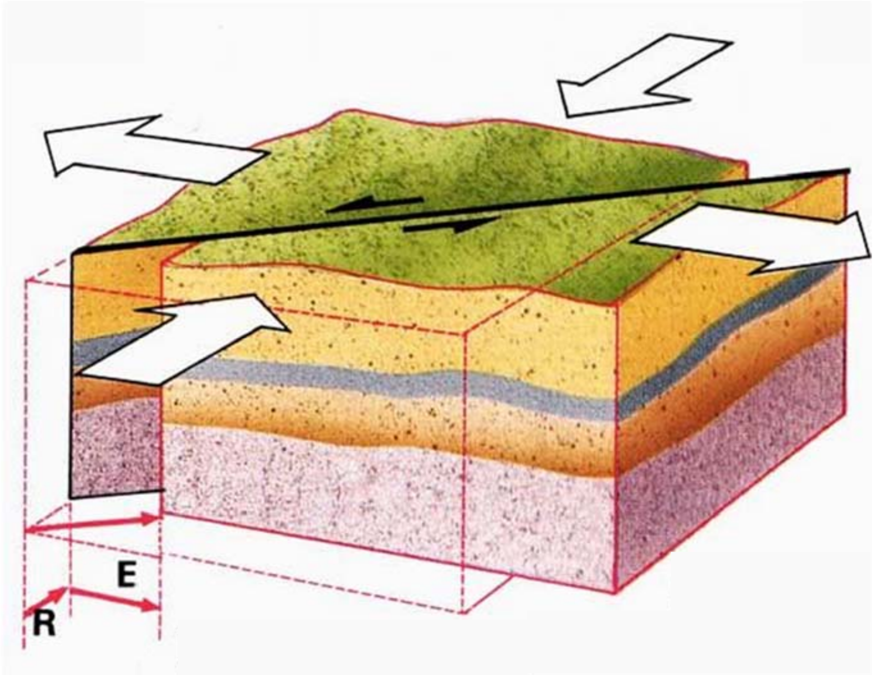


Fold & thrust



Faulted fold structure

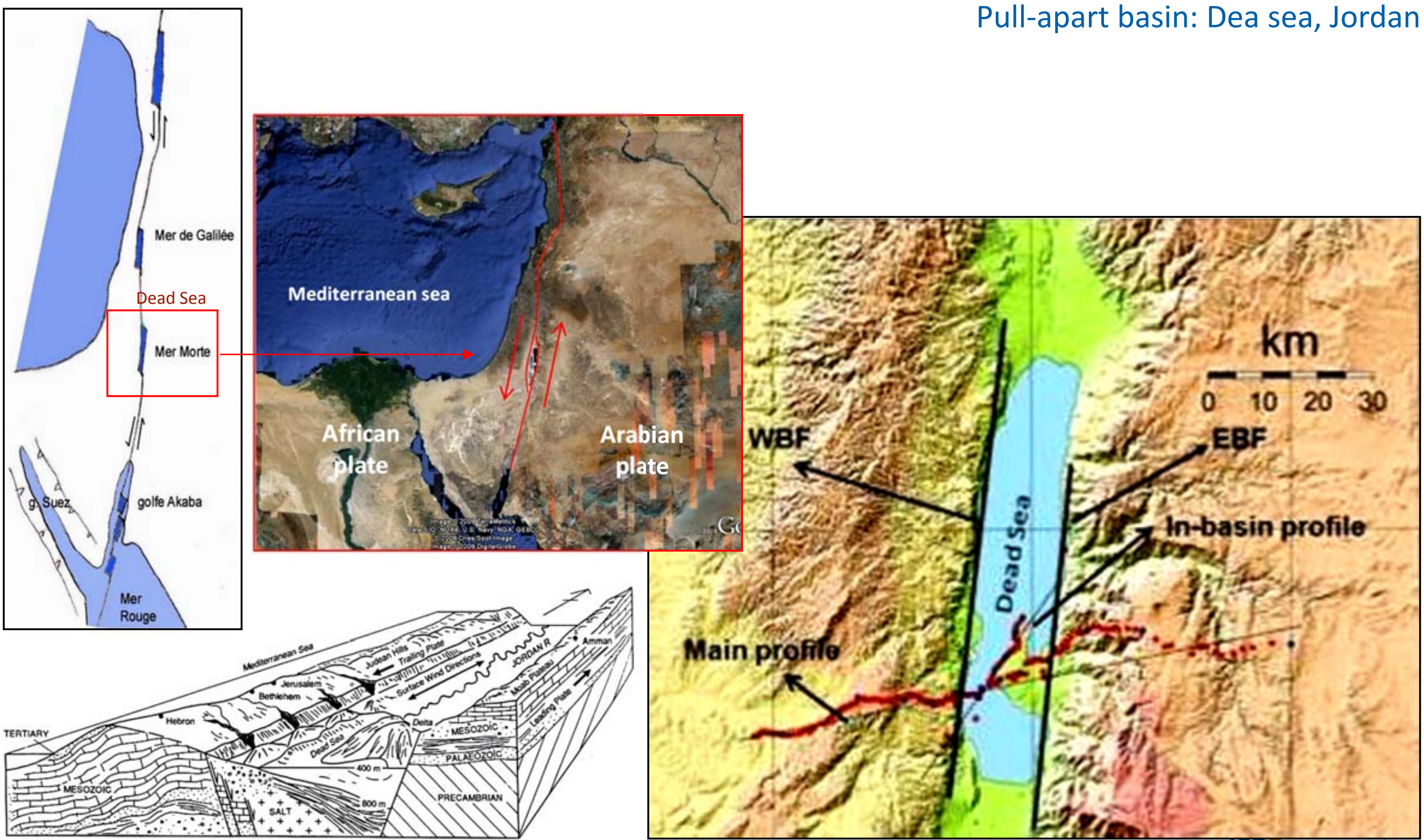
Shear: strike-slip faults



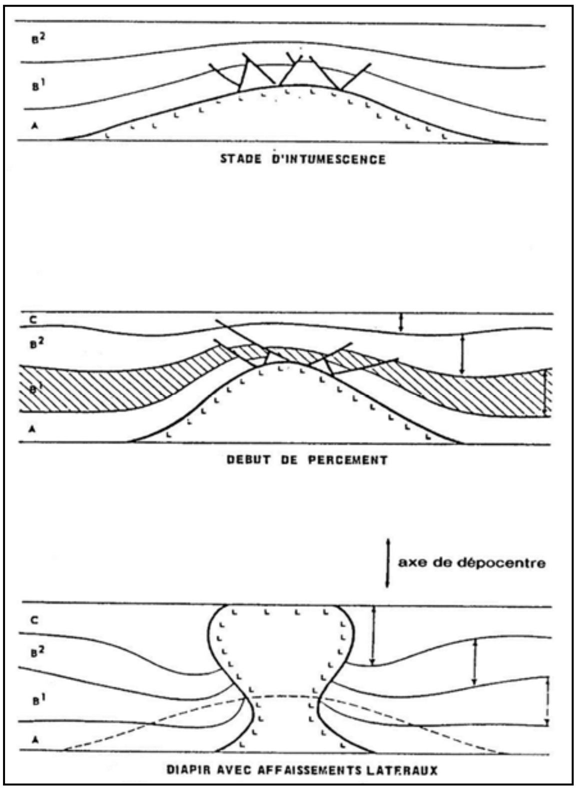
Shear: strike-slip faults

Strike-slip basins: examples

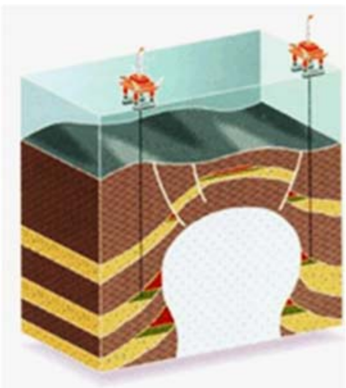
Pull-apart basin: Dea sea, Jordan

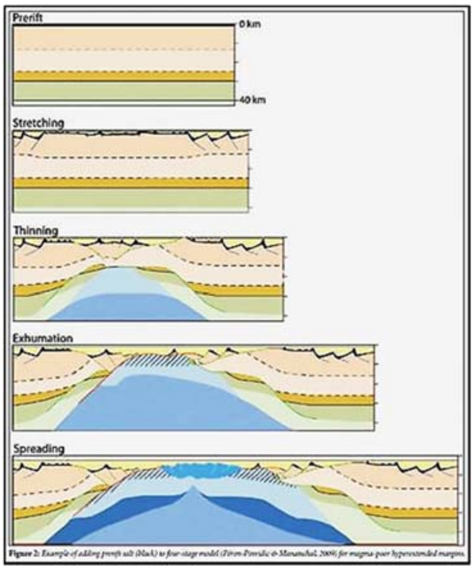


Salt tectonics: salt dome (diapir) evolution

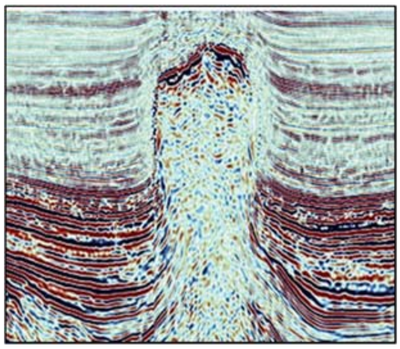


Constant salt volume
(except during last stage: dissolution)





Typical salt dome geometry
(seismic section)

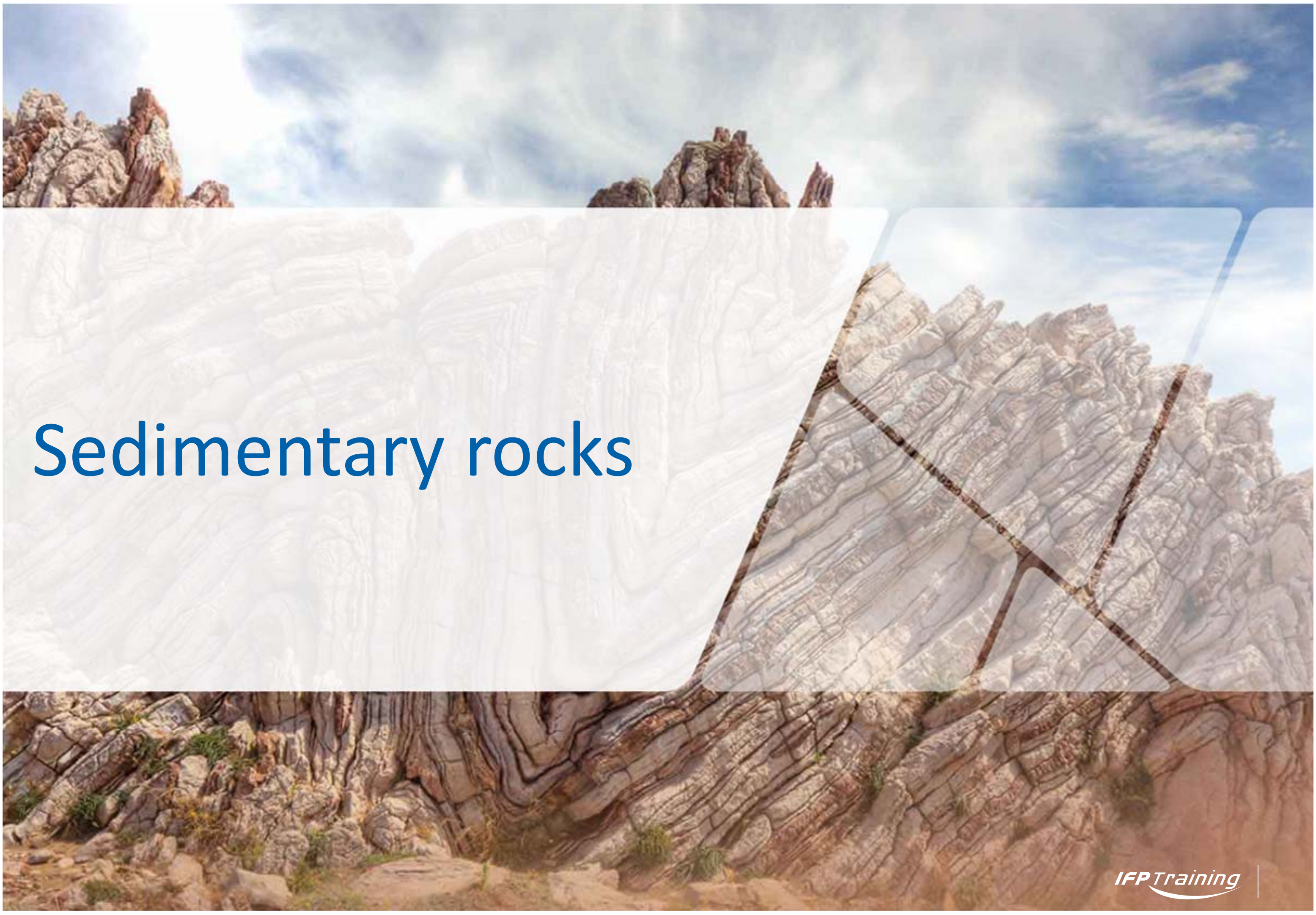


Structural geology: key points

- Some zones of the globe are in extension, others in compression: this defines the style of crustal deformations
- These relative movements generate regional constraints that are the source of crustal deformations
- Under the action of regional constraints, sediments and rocks undergo variable deformation, either ductile (folds) or brittle (faults)
- Two types of ductile deformation (folding):
  - Anticline [convex]
  - Syncline [concave]
- Three types of brittle deformation (faulting):
  - Normal (extension)
  - Reverse (compression)
  - Strike-slip (shearing/sliding)

End Day#1

Notes



Sedimentary rocks

II

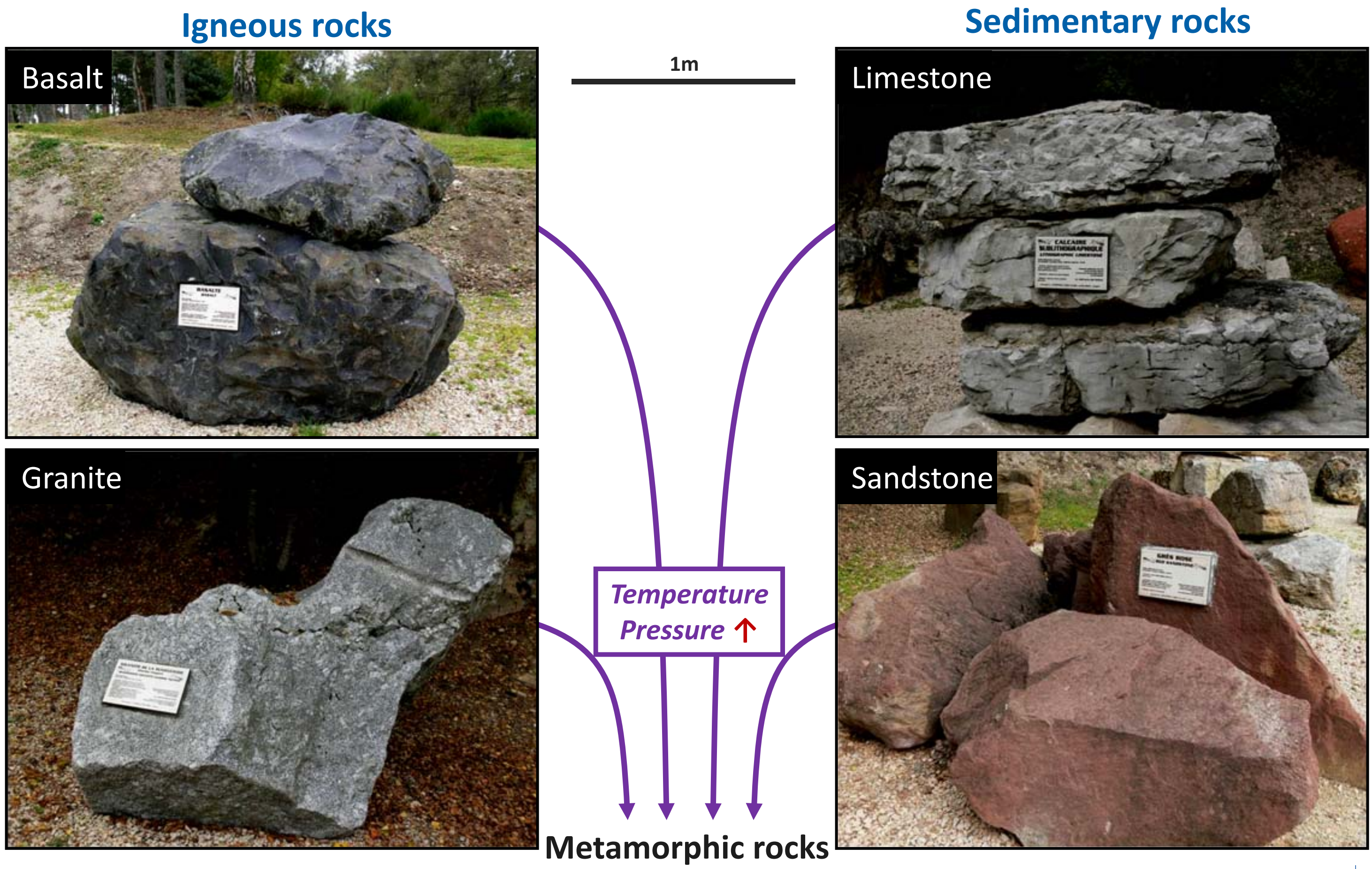
- Rock definitions - Specificity of sedimentary rocks
- Clastic rocks
- Carbonatic rocks
- Evaporitic rocks
- Organic rocks

Rocks: definitions

Three types of rocks on Earth:

- **Magmatic (igneous) rocks**
  - Formed by cooling and crystallization of magmas:
  - slowly, at great depth: plutonic rocks (e.g. granites) → Continental crust
  - quickly, at shallow depth or surface: volcanic rocks (e.g. basalts) → Oceanic crust
- **Metamorphic rocks**
  - Formed by transformation of pre-existing rocks under elevated pressures and/or temperatures (e.g. schists, gneiss)
  - Recrystallized (i.e. recombination of existing minerals)
- **Sedimentary rocks**
  - Formed at surface:
  - by mechanical processes, i.e. erosion of pre-existing rocks, transportation and deposition (e.g. sandstones, shales)
  - by chemical / biochemical processes (e.g. precipitation) followed by moderate depth burial (e.g. limestones)

Rock samples



Specificity of sedimentary rocks

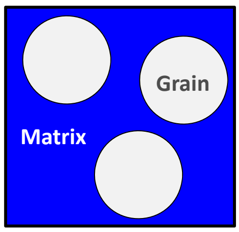
Sedimentary rocks:

- **are the only formations that can generate and accumulate hydrocarbons**
- **form at the surface of the Earth, by accumulation of particles** (weathered minerals, debris, …) **, or by chemical precipitation**
- **represent only 5% of the Earth's crust volume but cover 75% of its surface**
- **generally deposit as successive layers** (strata, bedding)

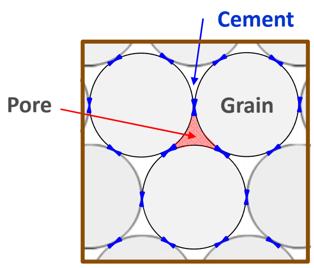
Characteristics of sedimentary rocks

Sedimentary rock characteristics:

- **Grains**
  - Mineralogy
  - Grain size (granulometry)
  - Grain shape (morphology)
  - Sorting
- **Pores** (void spaces)
  - Porosity (percentage of void volume > various types of porosity)
  - Effective porosity (interconnected voids)
  - Permeability (ability to allow a fluid to flow)
- **"Matrix"**
  - Matrix (primary binding material, deposited with grains)
  - Cement (secondary binding material, deposited after sedimentation, i.e. diagenetic)



Matrix ≈ 75%
Grain: 25%
Φ ≈ 0%



Grain ≈ 75%
Matrix ≈ Ɛ% (cement)
Φ ≈ 25%

➢ **Reservoir parameters !**

Classification of sedimentary rocks

- **Clastics**
  Accumulation of debris (alteration, weathering, erosion, destruction)
  - Conglomerate
  - Sand (sandstone)
  - Clay (shale)
- **Carbonates**
  Chemical precipitation or bio-fixation of dissolved calcium carbonate in water
  - Limestone
  - Dolomite
- **Evaporites**
  Salt deposition from highly concentrated brines (partial or total water evaporation)
  - Anhydrite
  - Halite
- **Organics**
  Fossilization of organic matter (deposition and preservation)
  - Coals
  - Kerogen

Notes

Sedimentary rocks

- Rock definitions - Specificity of sedimentary rocks
- Clastic rocks
- Carbonatic rocks
- Evaporitic rocks
- Organic rocks

Definition of silici-clastic rocks

- **Siliciclastics are detrital sediments resulting from the accumulation of debris from erosion / alteration / weathering of existing outcropping rocks.**
- **The main mineral components are quartz (SiO_2), feldspars, micas and clays.**
- **Clastic rocks are classified according to their grain size and shape:**
  - Conglomerates / Breccias
  - Sandstones
  - Siltstones
  - Shales (Claystones)
  - (Sandy and shaly sediment family)

Formation of clastic rocks

- **Weathering and erosion** (of outcropping rocks)
  - Chemical weathering (alteration)
    Agent: rain (+ dissolved CO_2)
    - solutions
    - grains
  - Mechanical weathering (erosion)
    Agents: gravity, freeze/thaw, running water, wind, glaciers
    - Block, grains, particles
- **Transport** (of debris + solutions and colloidal particles)
  Agents:
    - continental: water (torrents, streams & rivers), wind, ice (glaciers)
    - oceanic: currents, waves, tides, gravity flow deposits
- **Deposition**
  - Progressive decrease of current speed leads to deposition of transported load, with resulting sorting according to grain weight (and size)

Grain size classification

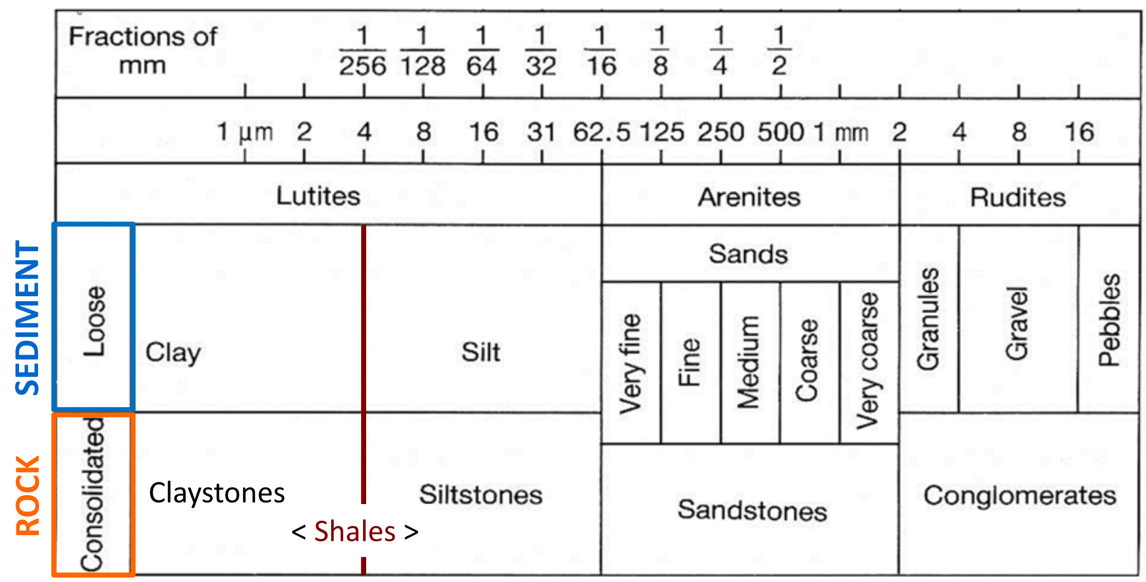
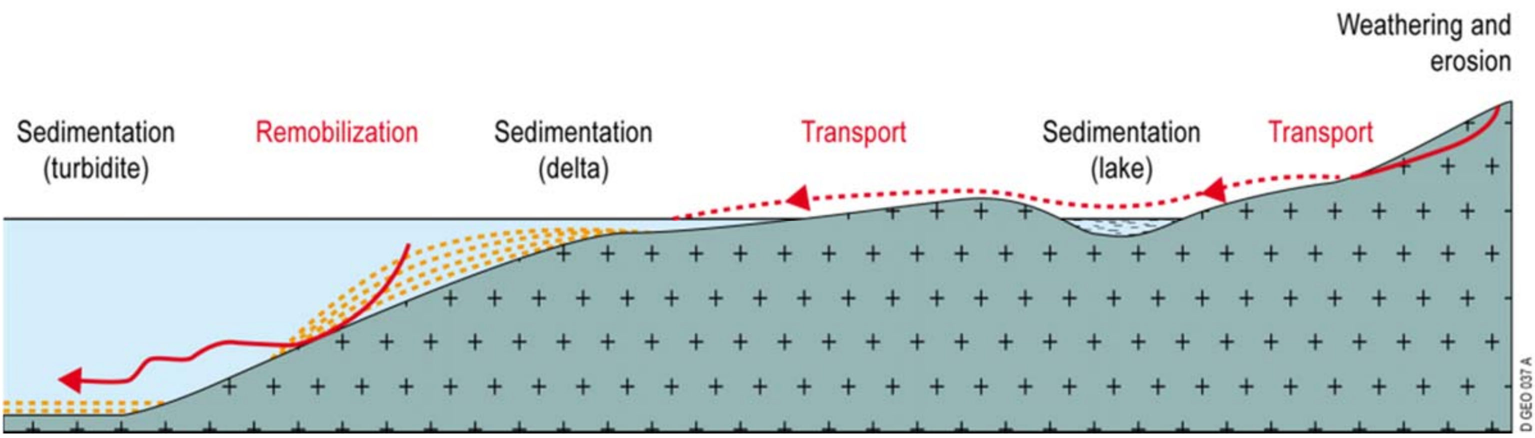


Table showing classification of granulometric classes

The grain-size are given in mm or µm, fractions of mm

Clastic rocks classification is complex because several variables are involved. Particle size (both average size and range of particles sizes), particles composition, cement and matrix type must all be taken into consideration. Shales (mostly clay minerals) are generally further classified according to composition and bedding.

Deposition of clastic sediments



Burial and compaction

Lithification

Final deposition → Diagenesis → Sedimentary rocks:

Increasing depositional energy

- **Conglomerates**
- **Sandstones**
- **Siltstones**
- **Shales**

Potential reservoirs

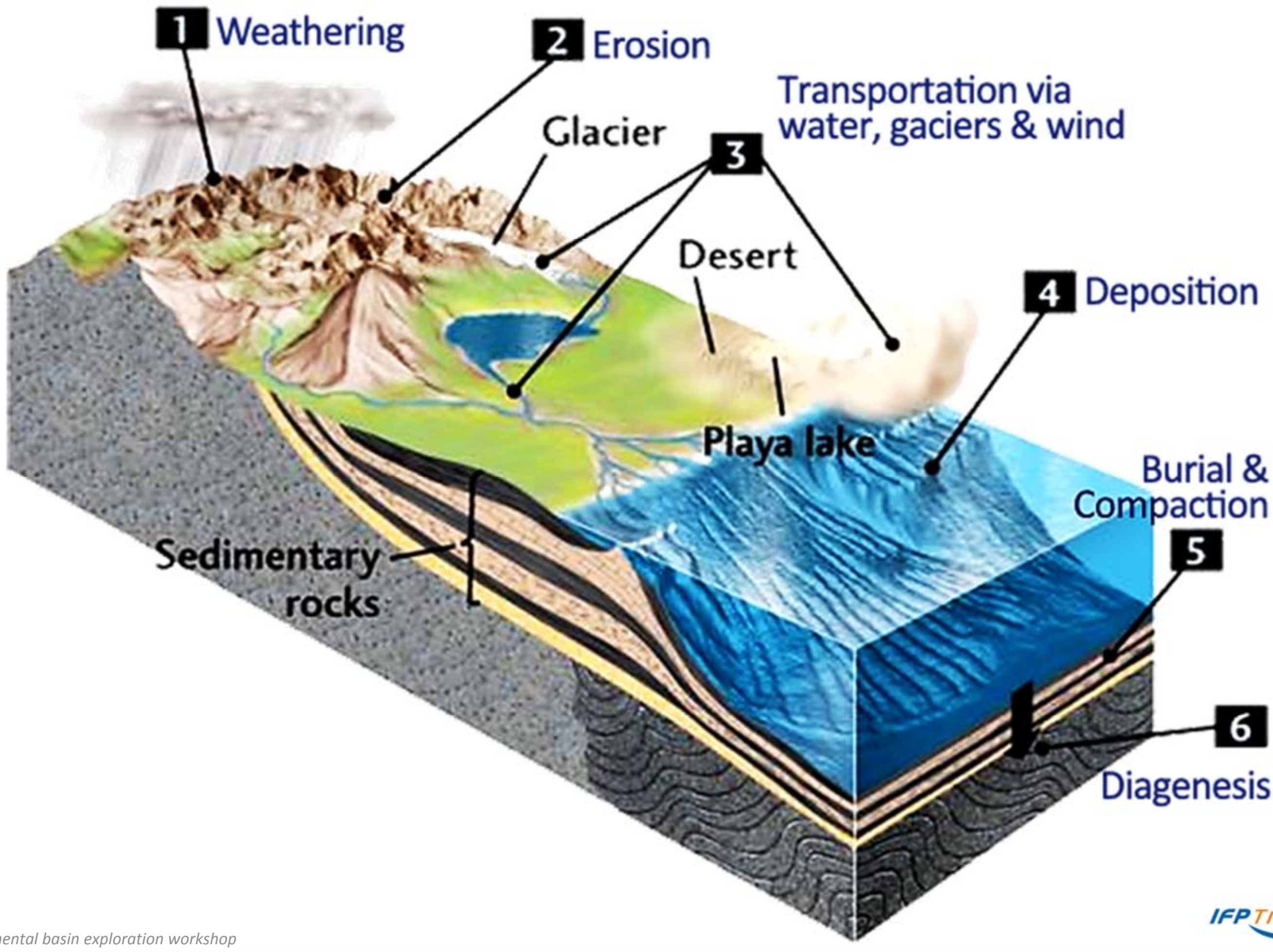
Potential seals

Low energy

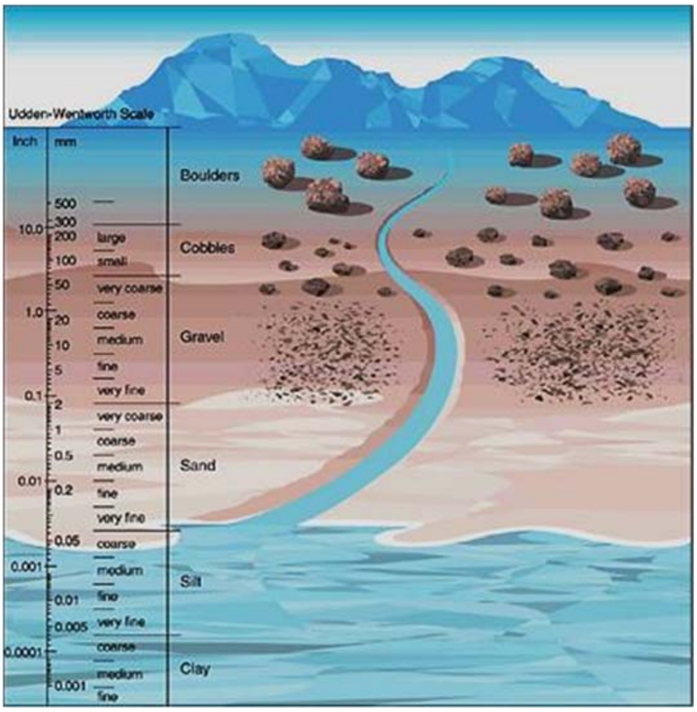
Allochthonous sediments

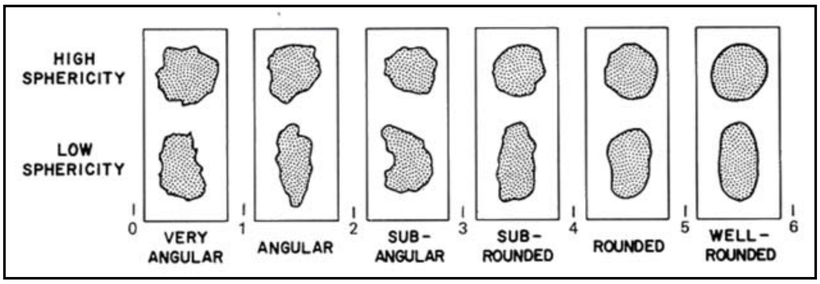
Mechanical rocks

Clastic depositional environments

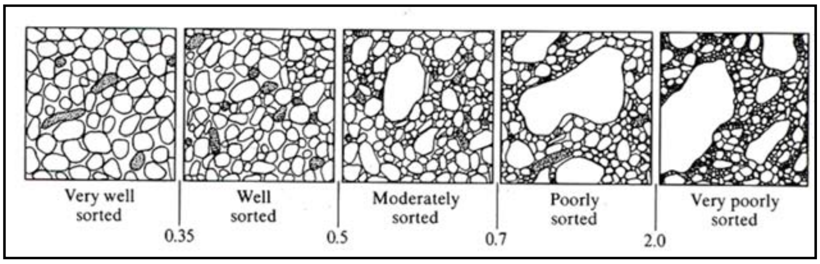


Clastic depositional processes





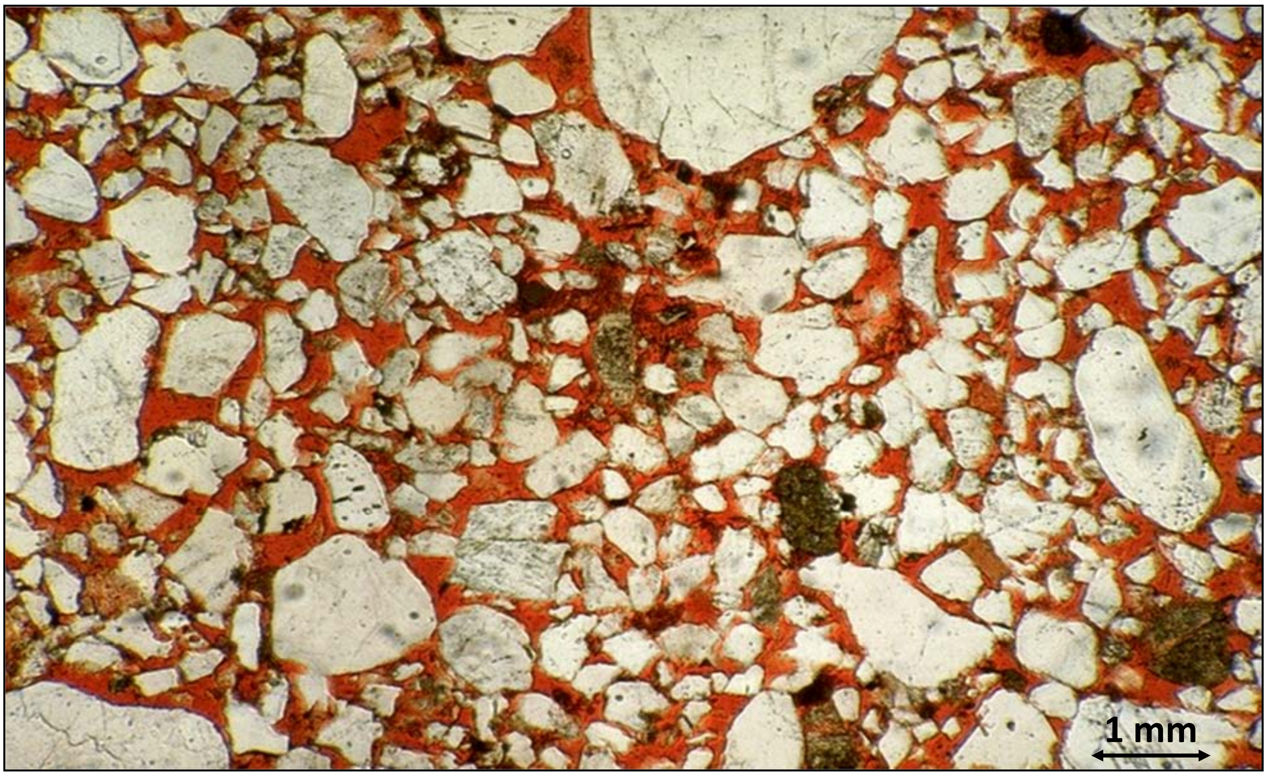
Evolution of sediments size, shape and sorting with distance (transport)



Fluvial clastic rock outcrop

Triassic Sherwood sandstones
(basal conglomerates)

Clastic rock thin section



Sandstone – White: grains (quartz), Red: pores (resin)

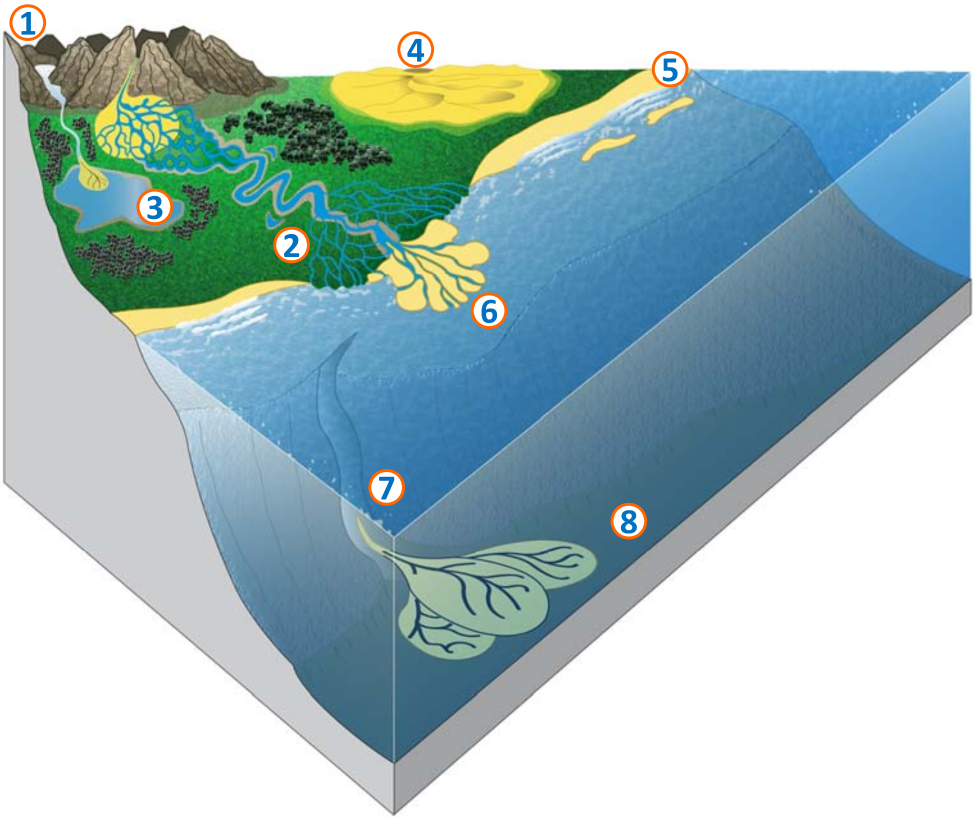
Clastics

- **Clastic sediments are:**
  - Allochthonous erosional products (weathering, alteration and transportation)
  - Transported by fluvial water, wind, ice
  - Deposited in basins
- **The main depositional process of clastic sediments is progressive deposition due to gradual decay of flow velocity (water or density current), i.e. decreasing transport energy**
- **Fluvial, deltaic and turbiditic depositional sequences are mostly fining-upward**
- **The evolution of a fluvial system involves both erosional and decantation processes (e.g. meander)**
- **The development of a delta is mostly due to progradation (if constant sediment supply and sea level)**
- **The main source of continental sediments is erosion of outcropping rocks**
- **The main sources of deep sea deposits are reworked existing sediments (e.g. from deltas)**

Clastic depositional environments

Continental

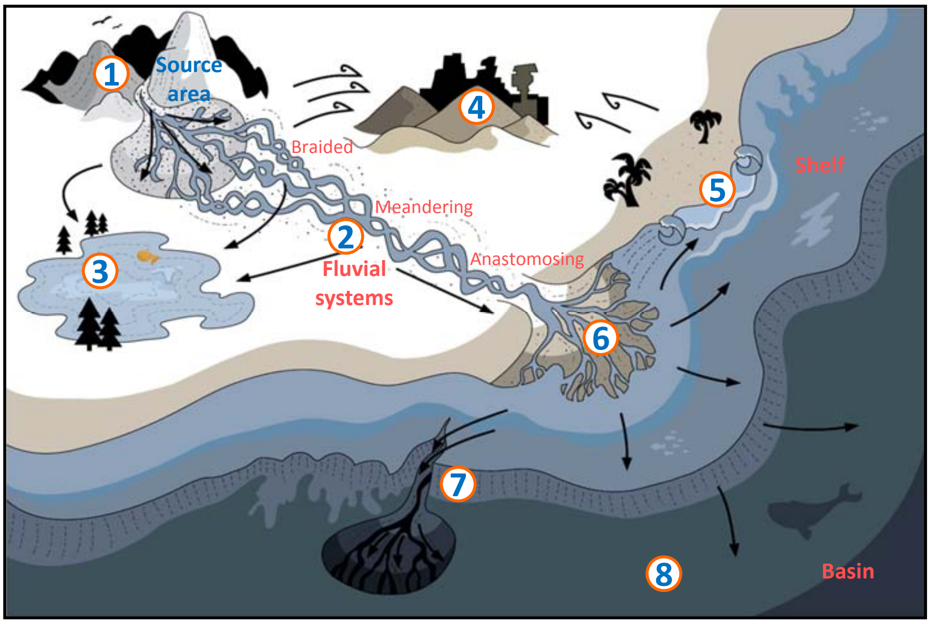
1. **Glacial**
2. **Fluvial**
   - Alluvial fan
   - Braided
   - Meandering *(point bar, crevasse splay)*
   - Flood plain *(oxbow lake)*
   - Anastomosing *(channel levee)*
   - Coastal plain *(swamp)*
3. **Lacustrine**
4. **Eolian** *(dunes)*

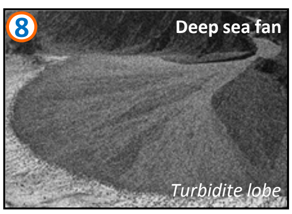


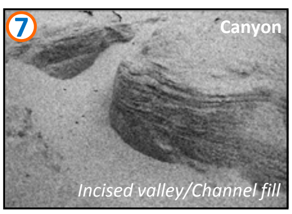
Marine

5. **Shoreline** *(coast/beach)*
6. **Delta**
   - Fluvial-dominated
   - Wave-dominated
   - Tide-dominated
7. **Slope, canyon**
8. **Basin**
   - Deep sea fan *(Turbidite)*
   - Abyssal plain

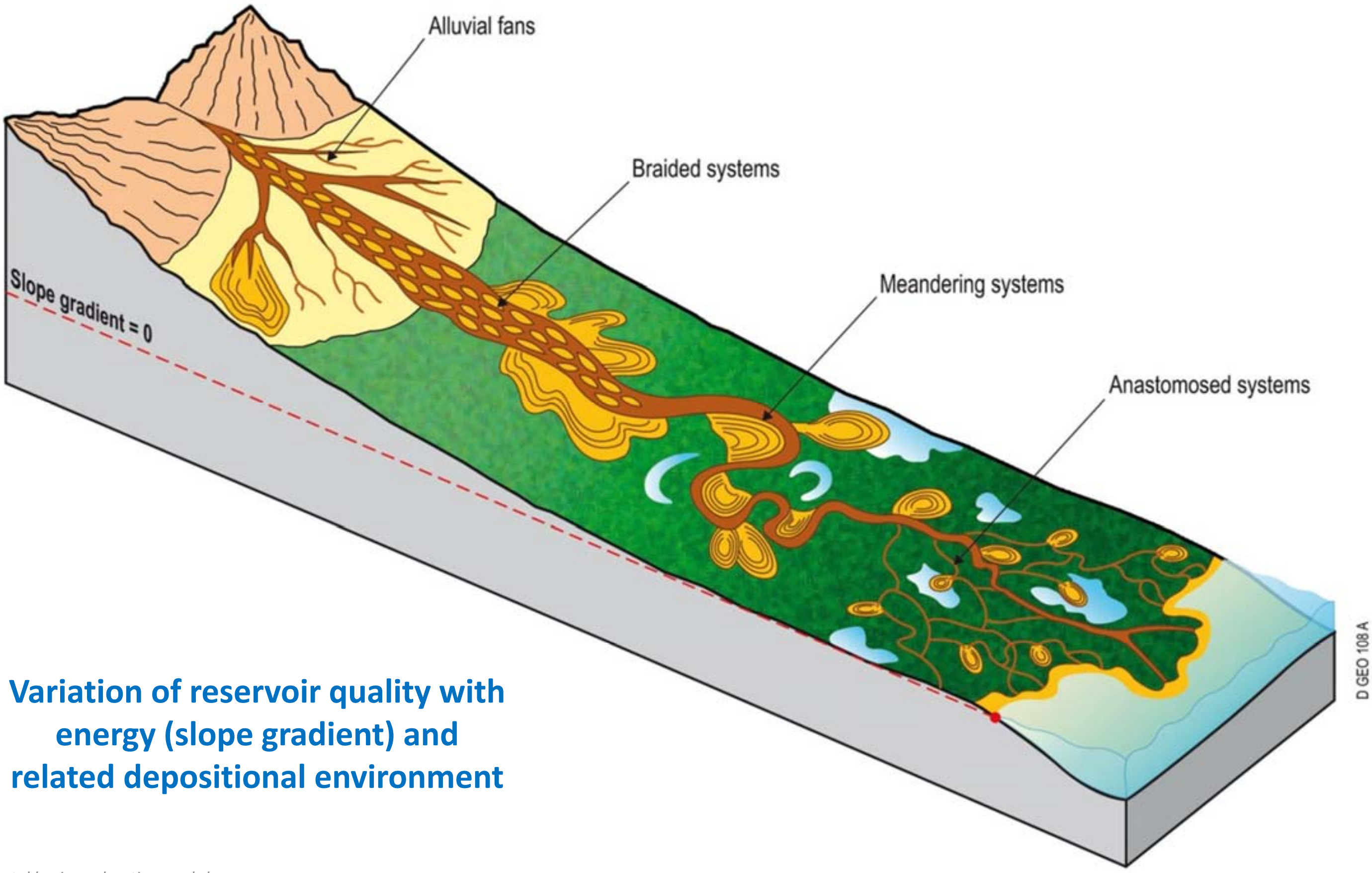
Clastic depositional environments







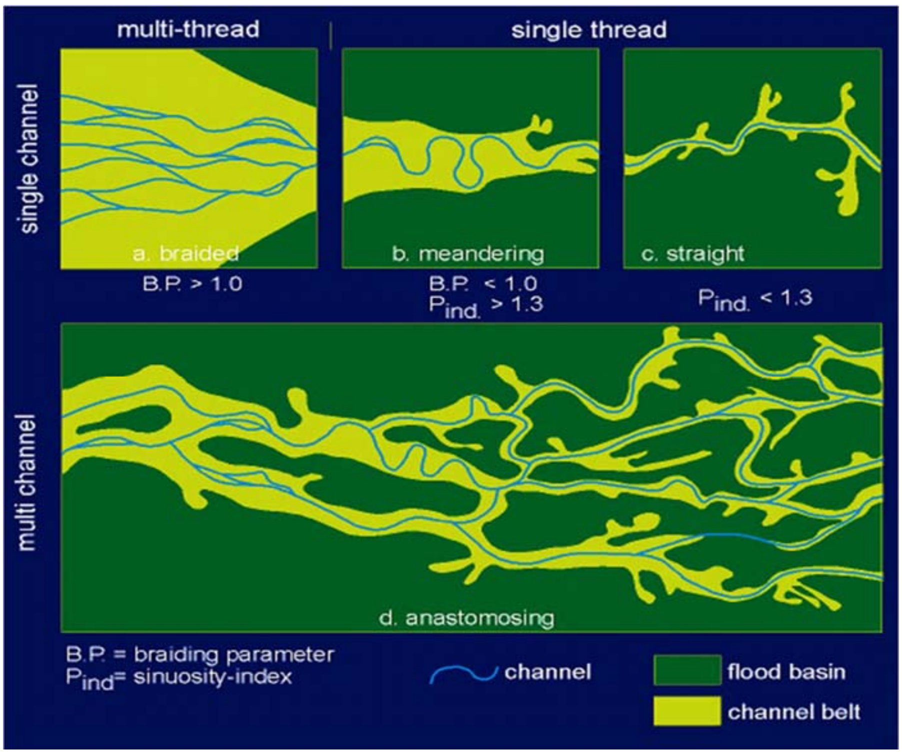
Fluvial siliciclastic environments



Variation of reservoir quality with energy (slope gradient) and related depositional environment

Fluvial depositional settings

- **River channel pattern is the combination of**
  - Bedload vs suspended load
  - Slope gradient
  - River bank (levee) stability
  - Flow fluctuations
- **Downslope decrease of**
  - Slope gradient
  - Entrenchment
  - Stream power
  - Grainsize
  - Bedload
- **Downslope increase of**
  - Channel stability
  - Network organization
  - Grain sorting
  - Flow steadiness

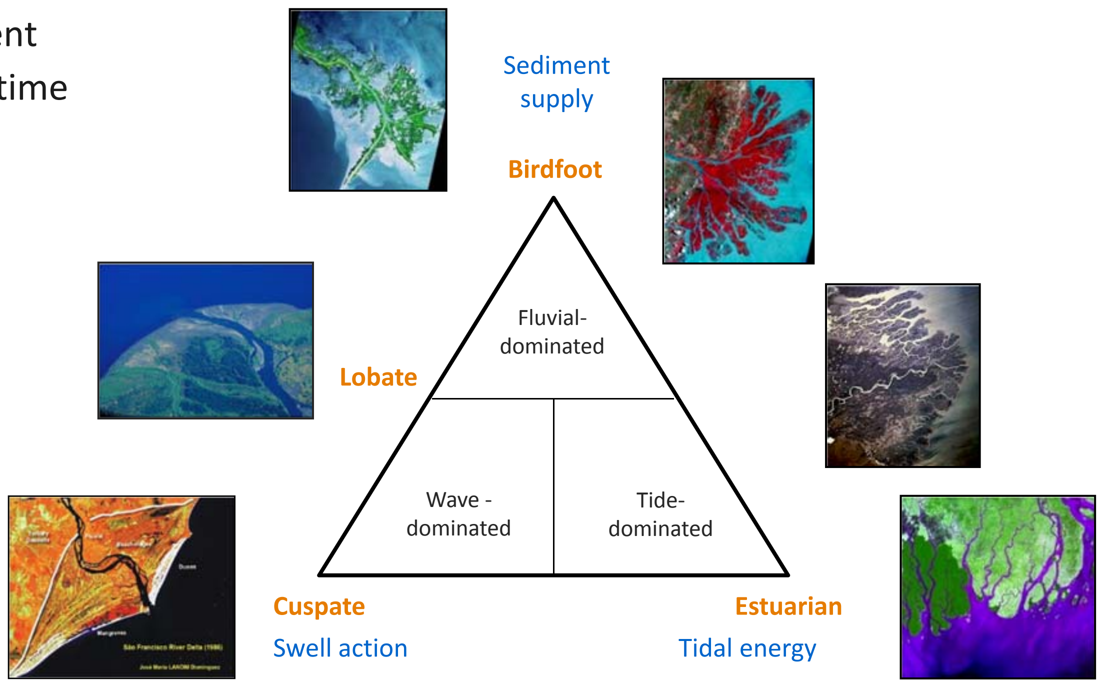


River facies vs Reservoir geometry

Courtesy: Pr. M. Lopez (U. of Montpellier)

Delta shapes & energy

- **Morphological classification of deltas based on delta front shape which reflects:**
  - Relative importance of river, tide or/and wave processes
  - Sediment supply
  - Slope gradient
  - Duration in time



Sedimentary rocks

- Rock definitions - Specificity of sedimentary rocks
- Clastic rocks
- Carbonate rocks
- Evaporitic rocks
- Organic rocks

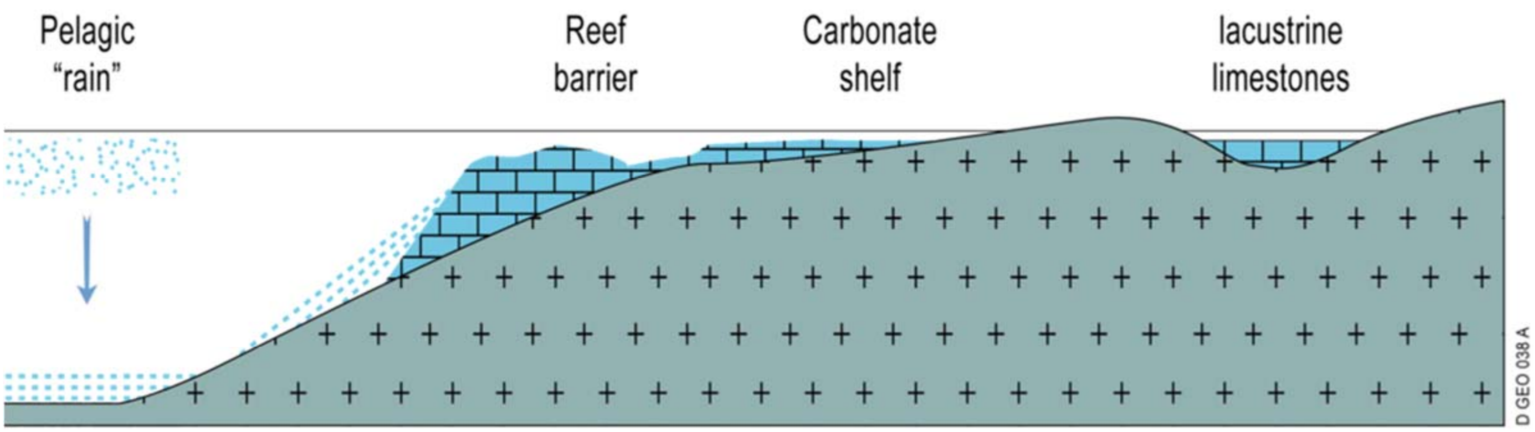
Definition of carbonate rocks

- **Carbonate sediments result from chemical precipitation and from fixation by living organisms of the calcium carbonate dissolved in the water**
- **Chemical composition of carbonatic sediments:**
  - $CO_2 + H_2O = H_2CO_3 = H^+ + HCO_3^- = CO_3^{--} + 2\ H^+$
  - $CO_3^{--} + Ca^{++} = CaCO_3$ (i.e. calcite or aragonite)
- **Two main types of carbonates:**
  - Limestone (Ca CO_3 : calcium)
  - Dolomite (Ca,Mg CO_3 : calcium–magnesium)
- **They are very important prospects**

Formation of carbonate rocks

- **Chemical precipitation**
  - Equilibrium variation of soluble calcium carbonate in water.
    Factors can include:
    - Relative CO_2 pressure in the atmosphere
    - Water parameters:
      - temperature
      - salinity
      - agitation (energy)
    - Amount of vegetal and animal life
- **Biochemical fixation**
  - Fixation of carbonate in the skeleton of living organisms (e.g. plankton, shells)
  - Death of organisms > decantation of corpses
  - Sedimentation and preservation (variable) of skeletons

Deposition of carbonatic sediments



Burial and compaction *Lithification*

Final deposition → Diagenesis → Sedimentary rocks:

Increasing depositional energy

- **Grainstone**
- **Packstone**
- **Wakestone**
- **Mudstone**

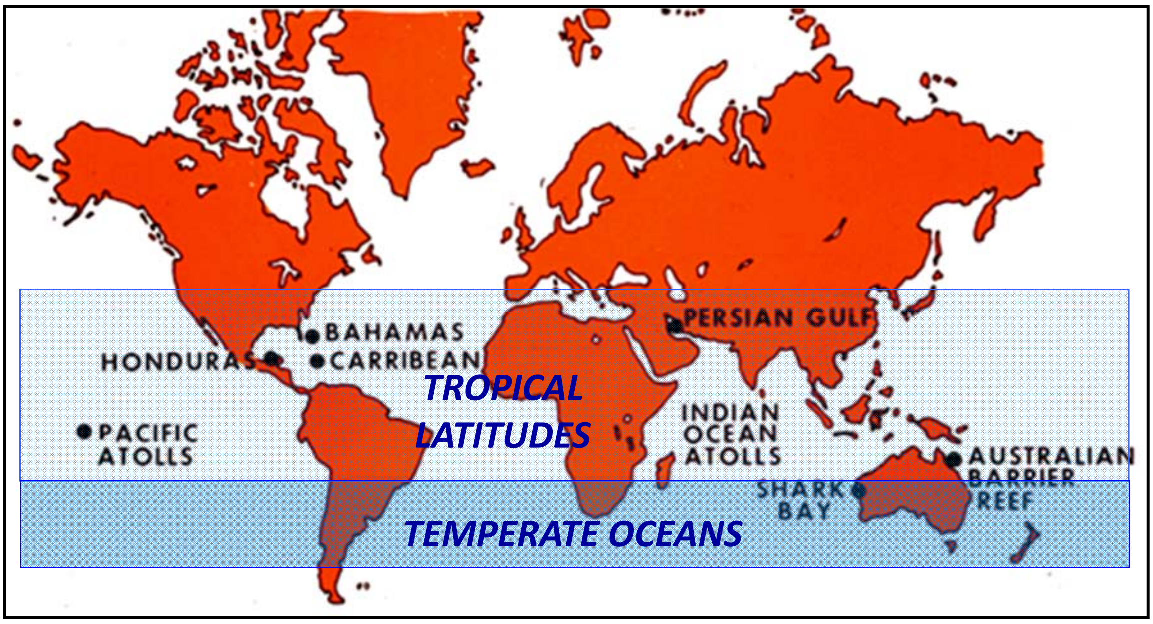
Low energy

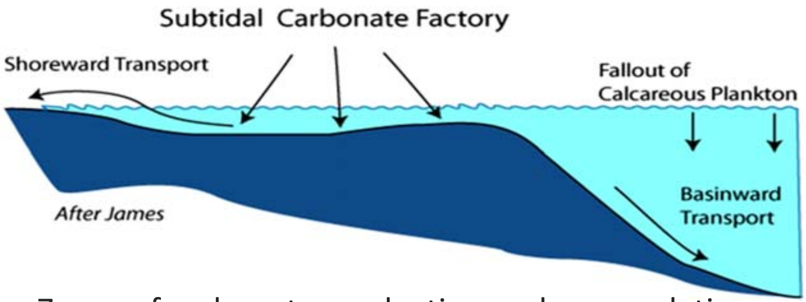
Potential reservoirs

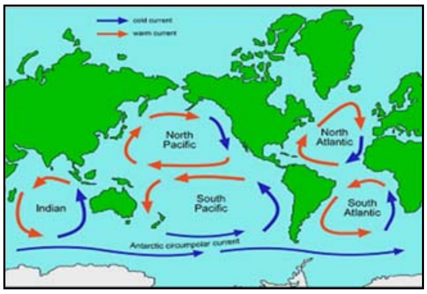
Potential seals

Autochthonous sediments
Chemical rocks

Carbonate depositional areas



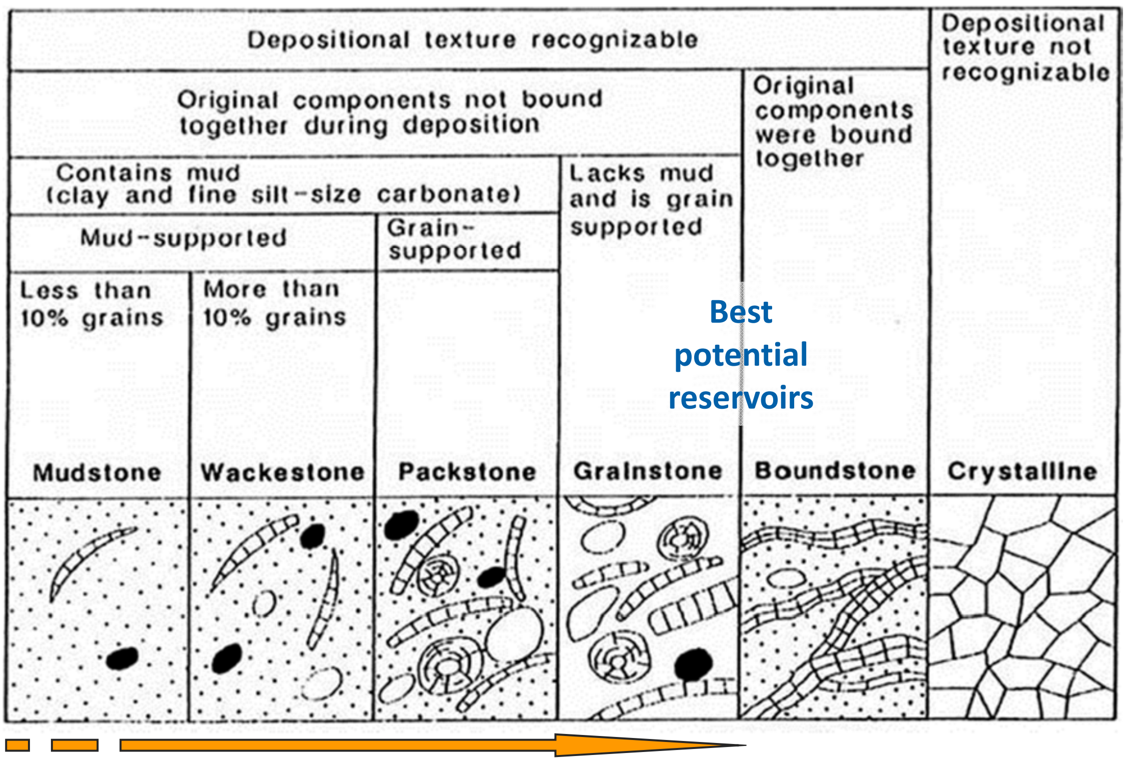




Zones of carbonate production and accumulation

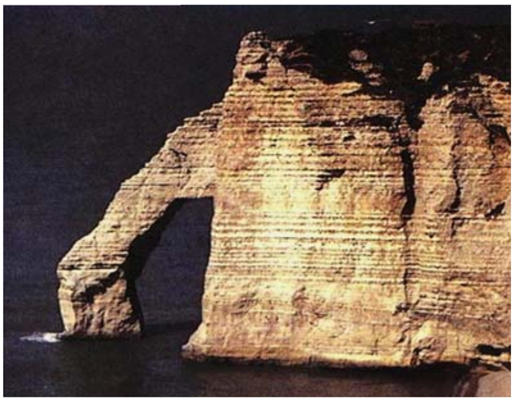
Classification of carbonates

Dunham's textural classification of carbonate rocks



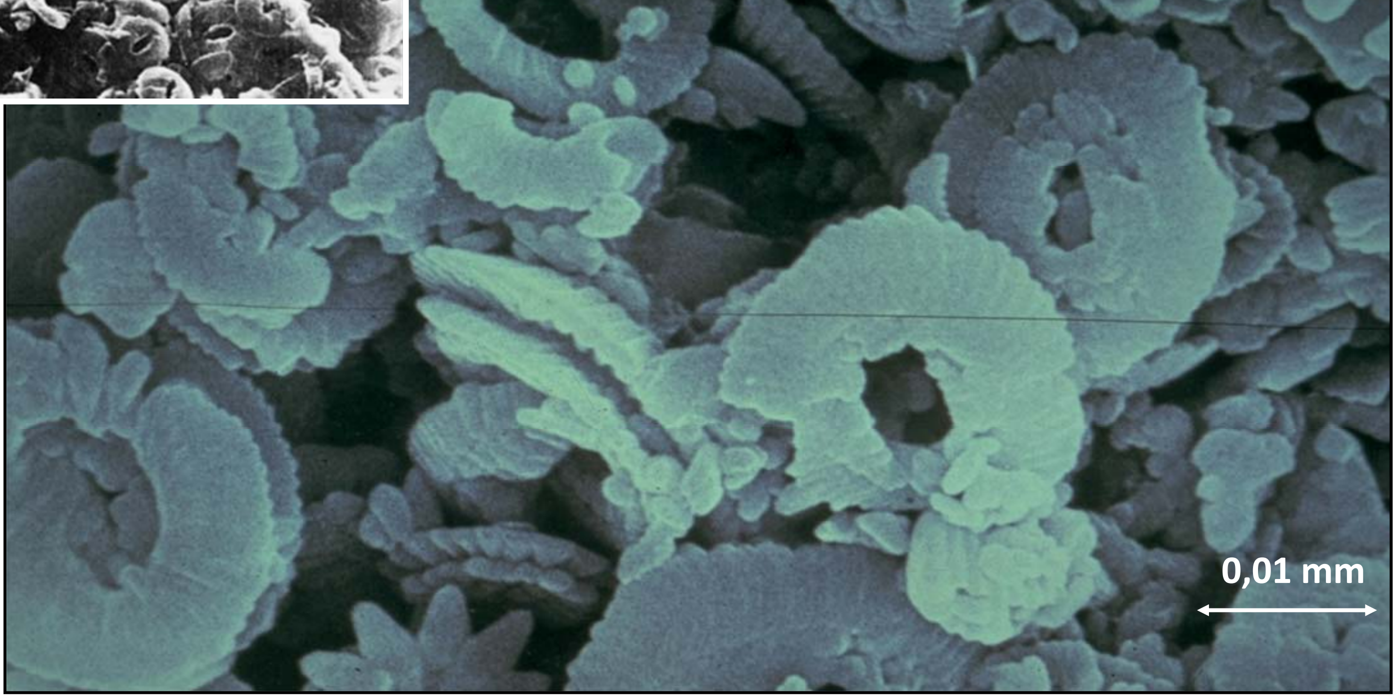
Increasing depositional energy

Carbonate rock outcrop



Chalk cliffs – Etretat, France

Carbonate rock (scanning electron microscopy)



Chalk (Coccolites)

Sedimentary rocks

- Rock definitions - Specificity of sedimentary rocks
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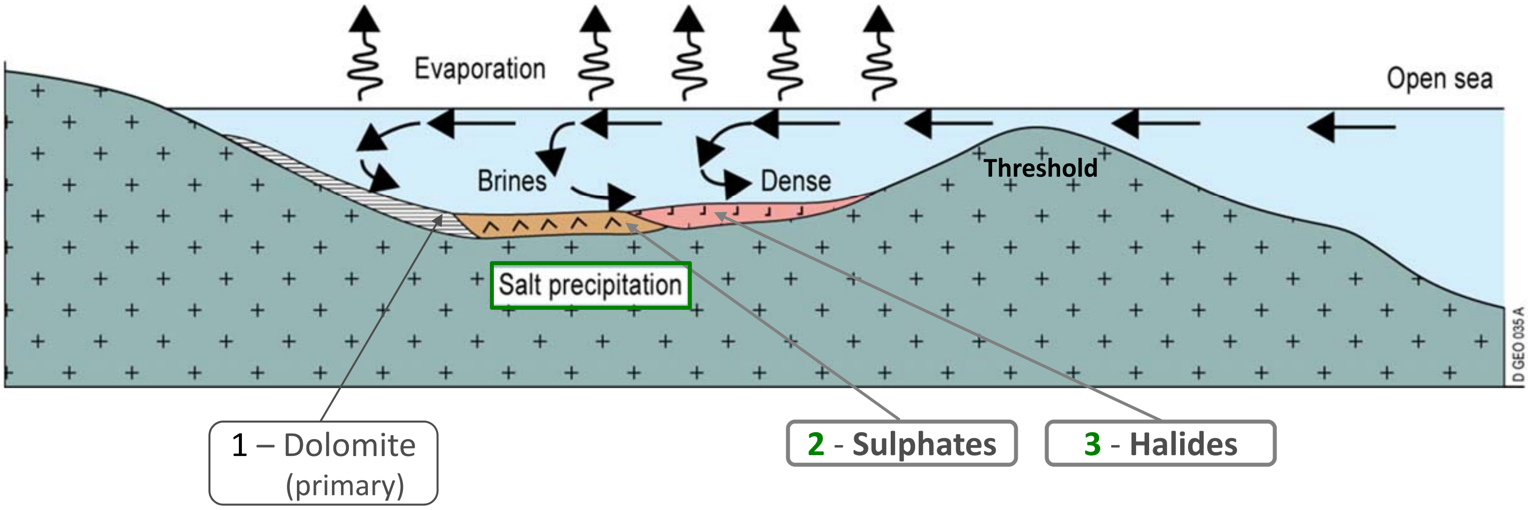
- Carbonatic rocks
- Evaporitic rocks
- Organic rocks

Definition of evaporites or salt rocks

- **Partial or total water evaporation can generate rocks from highly concentrated saline deposits (i.e. brines).**
- **These chemically produced rocks are called evaporites because they result from salt precipitation due to the evaporation of brackish waters.**
- **Depending on water composition, they can be:**
  - Gypsum, Anhydrite (sulphates)
  - Halite, Sylvite (halides & chlorides)
- **Salt rocks can be good cap rocks (seals) for all hydrocarbon accumulations.**
- **They play a very important part in hydrocarbon systems evolution.**

Formation and deposition of evaporites



Salt rocks ➔ Potential seals (cap rocks)

Artificial and natural evaporitic accumulation


Salt plant ("marais salants")
Île de Ré, France


Uyuni salt lake, Bolivian cordillera (+4000m ss)


Dead sea, Jordan (-400m ss)

Sedimentary rocks

- Rock definitions - Specificity of sedimentary rocks
- Clastic rocks
- Carbonatic rocks
- Evaporitic rocks
- Organic rocks

Definition of organic rocks

- **Organic rocks come from the fossilization of the organic matter produced by living organisms (plants or animals)**
- **Depending on the origin of organic matter, they are called:**
  - Coal, anthracite, peat,…
- **Organic rocks are fundamental in the hydrocarbon domain:**
  - they are the source rocks of hydrocarbons

Plants = 90% of biomass

Kerogen = lithified organic matter after burial & compaction

Sedimentary rocks: summary

- **Clastics**
  - Transport and accumulation of weathered minerals or altered bio fragments
    - conglomerate, sandstone, shale [≠ grainsize]
- **Carbonates**
  - Chemical or biochemical precipitation of dissolved calcium carbonate
    - limestone, dolomite [≠ texture, composition]
- **Evaporites**
  - Salt deposition from concentrated brines (water evaporation)
    - sulphates, chlorides [≠ composition]
- **Organics**
  - Deposition and preservation (fossilization) of organic matter
    - coal, kerogen [≠ origin]

Sedimentary rocks - Key points #1

Nature and origin of sedimentary rocks

- **Accumulation of successive layers (stratification, bedding) of:**
  - transported minerals, on surface or in aquatic environments (fluvial, marine)
  - precipitated chemical elements (carbonates, evaporites)
  - decanted fossils: dead plant fragments or animal skeletons (carbonates, organics)
- **Sediment-to-rock processes**
  - Erosion of existing rocks
  - Transportation (solid) and/or solution
  - Sedimentation (deposition in topographic lows: basins)
  - Transformation during burial (diagenesis, lithification)

Clastics vs Carbonates – 1/2

Siliciclastic rocks

- **Origin**
  - Allochthonous sediments
  - Erosion, weathering and alteration of outcrops → Mechanical rocks
- **Transport**
  - Rivers, wind, ice
  - Over variable distances (up to +1000 km)
  - Grainsize decrease with distance from source
- **Deposition**
  - Environments: fluvial, coastal, shelfal, basinal
  - Depositional dynamics: variable, from high to low energy
- **Specificity**
  - 3 families: conglomerate, sandstone, shale (≠ grainsize)
  - Variable reservoir quality (good porosity and permeability for high energy deposits)

Carbonate rocks

- **Origin**
  - Autochthonous sediments
  - Deposition in situ (precipitation, bio-fixation or crystallization) → Chemical rocks
- **Transport**
  - None
  - Over short distances (high energy environments)
- **Deposition**
  - Environments: lacustrine, shelfal, basinal
  - Depositional dynamics: local conditions, from high to low energy
- **Specificity**
  - 2 types: Limestone ($CaCO_3$), dolomite (Ca, $MgCO_3$)
  - Variable reservoir quality (good porosity and permeability for high energy deposits)
  - Strong impact of chemical transformations after deposition (diagenesis) on reservoir properties

Clastics vs Carbonates – 2/2

Nature vs Texture

		TEXTURE [Energy]		
		Low E.	High E.	
		Mud [Boue] Water+Dust	Sand [Sable] Grains	Sediment
NATURE [Chemistry]	SiO2	Shale [Argile]	Sandstone [Grès]	Rock
	CaCO3	Mudstone	Grainstone	
		Bad reservoir	Good reservoir	

End Day#2

Notes

Notes

Petroleum systems

IFP Training

Petroleum systems

III

- **Structure of hydrocarbons**
- **Origin and generation**
- **The Petroleum Trilogy**
- **Migration**
- **Traps**

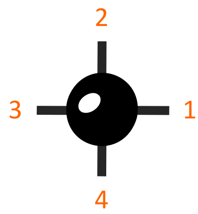
Hydrocarbons structure

HYDROCARBON

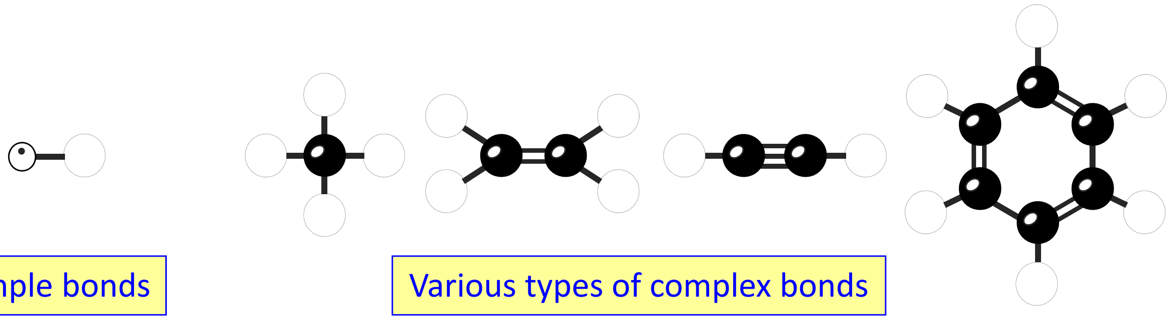
Hydrogen : H

Valence = 1

Carbon : C



Valence = 4

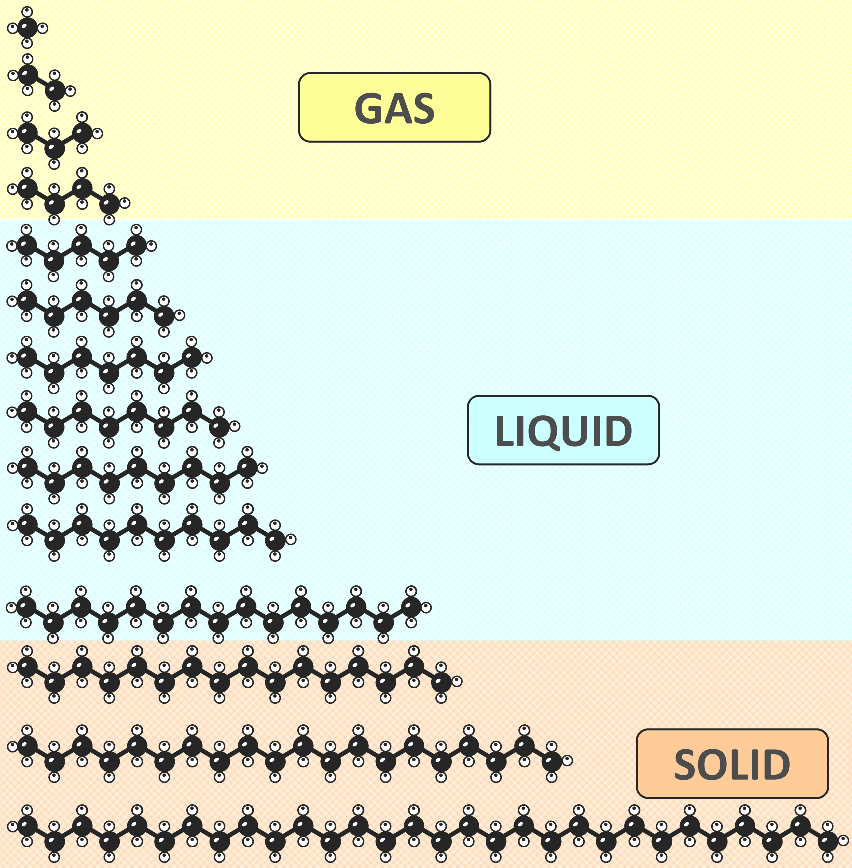


Simple bonds

Various types of complex bonds

Hydrocarbons classification

	Nb carbon atoms	Formula	density
Methane	C_1	C_1H_4	
Ethane	C_2	C_2H_6	⋮
Propane	C_3	C_3H_8	0,505
Butane	C_4	C_4H_{10}	0,585
Pentane	C_5	C_5H_{12}	0,631
Hexane	C_6	C_6H_{14}	0,664
Heptane	C_7	C_7H_{16}	0,688
Octane	C_8	C_8H_{18}	0,707
Nonane	C_9	C_9H_{20}	0,722
Decane	C_{10}	$C_{10}H_{22}$	0,727
⋮	⋮	⋮	⋮
Pentadecane	C_{15}	$C_{15}H_{32}$	0,766
Hexadecane	C_{16}	$C_{16}H_{34}$	
Eicosane	C_{20}	$C_{20}H_{42}$	
Tricontane	C_{30}	$C_{30}H_{62}$	



From light crude to heavy oil…

Petroleum systems

- Structure of hydrocarbons
- Origin and generation
- The Petroleum Trilogy
- Migration
- Traps

Origin of hydrocarbons

Transformation of organic matter (O.M.) from dead fauna or flora

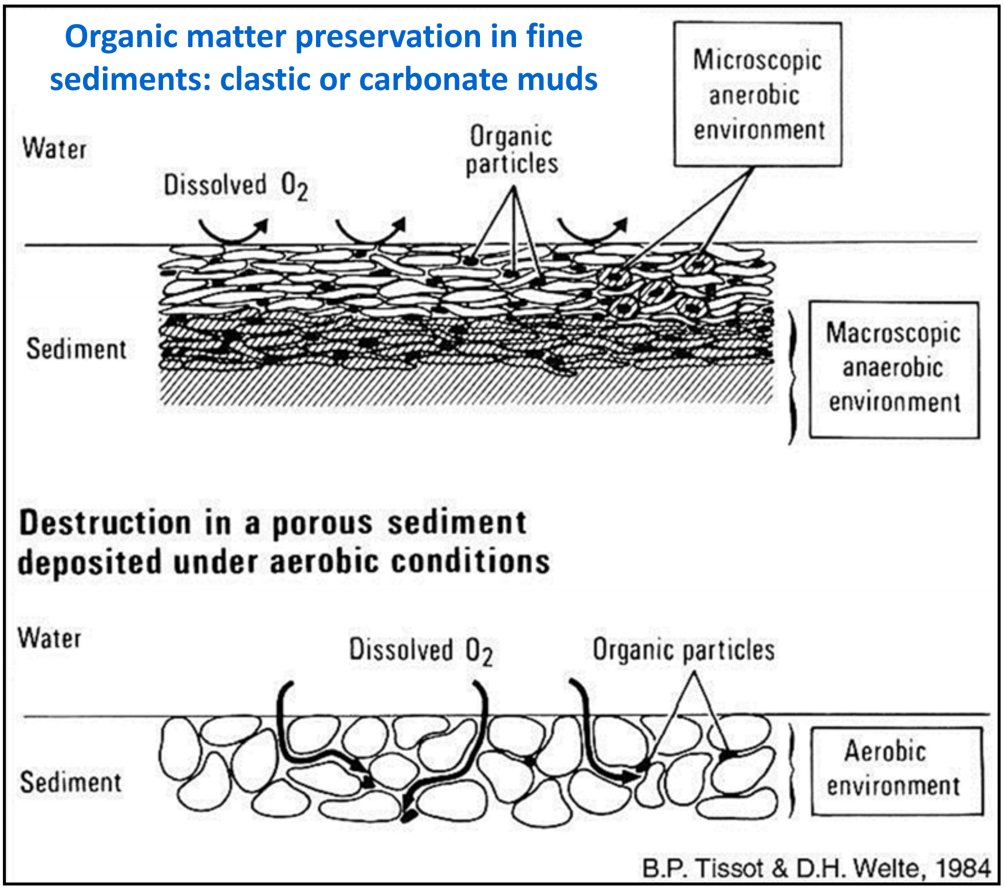
- **Accumulation & preservation of O.M.**
  - Accumulation in quiet geological environments (lake, delta, sea → muddy & anoxic environments)
  - Preservation depends on sediment type & rate, environment energy
- **Modification of depositional conditions**
  - Burial, compaction, water expulsion
  - Temperature & pressure increase
- **Transformation of Kerogen into hydrocarbons**
  - Oil
  - Gas (methane)

Kerogen: non soluble part of O.M. (i.e. lipids)

Maturation: chemical transformation, mainly due to temperature (and pressure) increase during burial

Source rock: rock with 1-10 % of kerogen which can eventually be transformed into hydrocarbons

Accumulation & preservation of O.M.

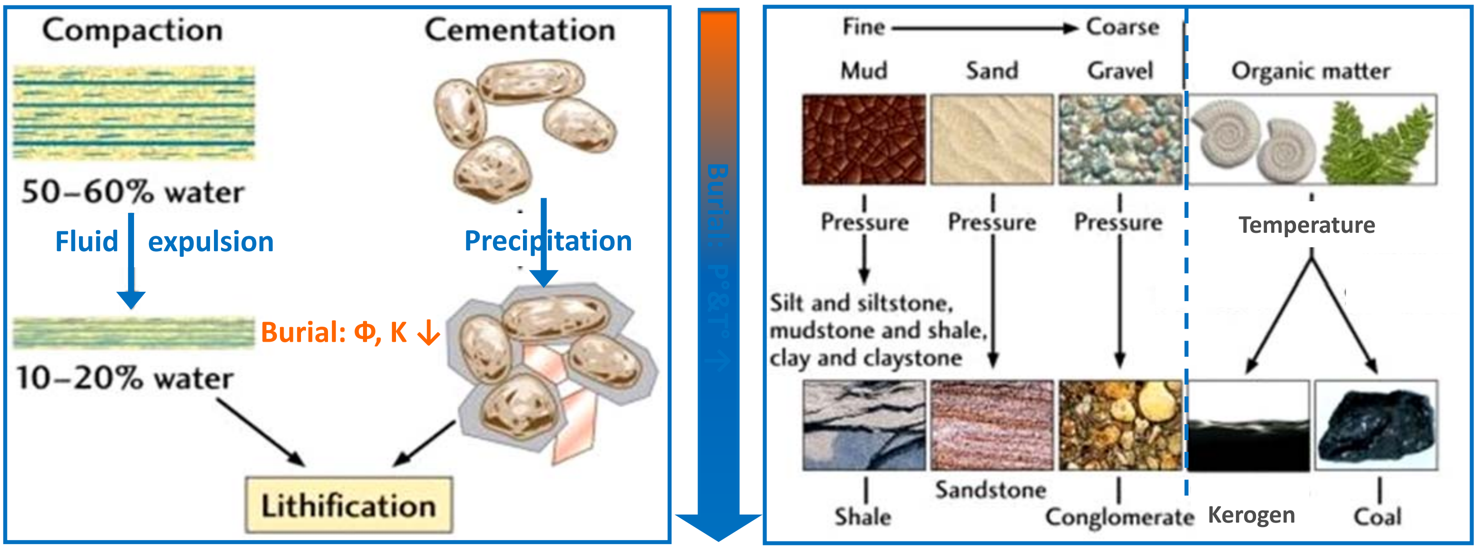


B.P. Tissot & D.H. Welte, 1984

Burial and diagenesis

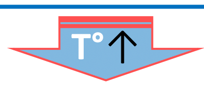
During burial, sediments are gradually turned into rocks

Compaction + Cementation [+ Diagenetic transformations] = Lithification



→ Both P° and T° increase with burial and depth

→ Both Φ and K decrease with burial and lithification

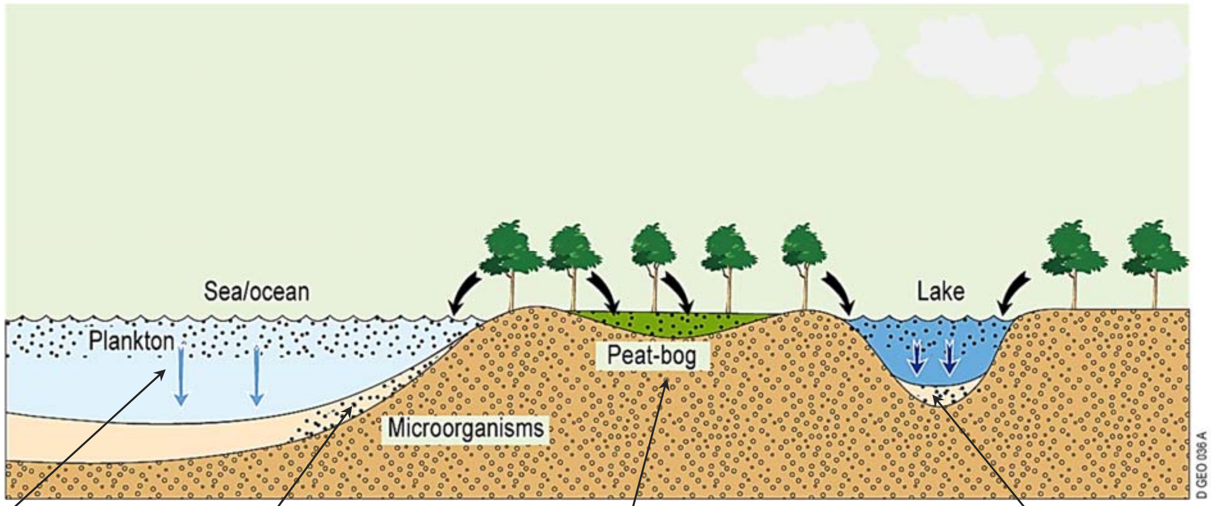


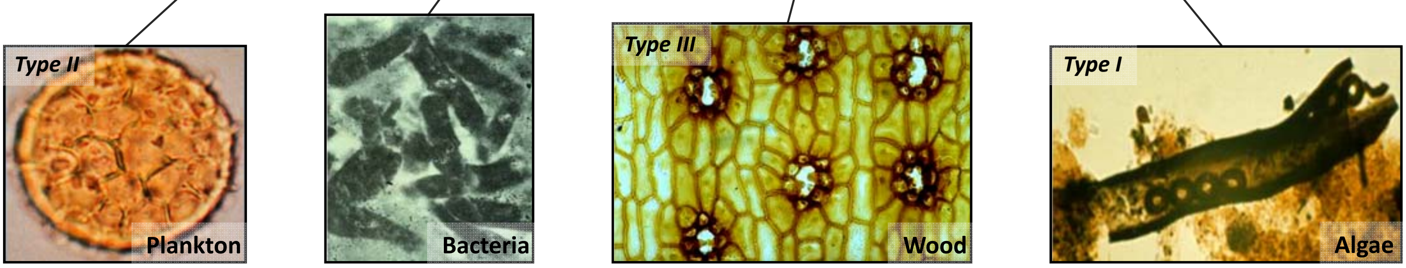
Hydrocarbons

Origin of organic matter (OM)

O.M.

- Lipids
- Cellulose
- Lignine





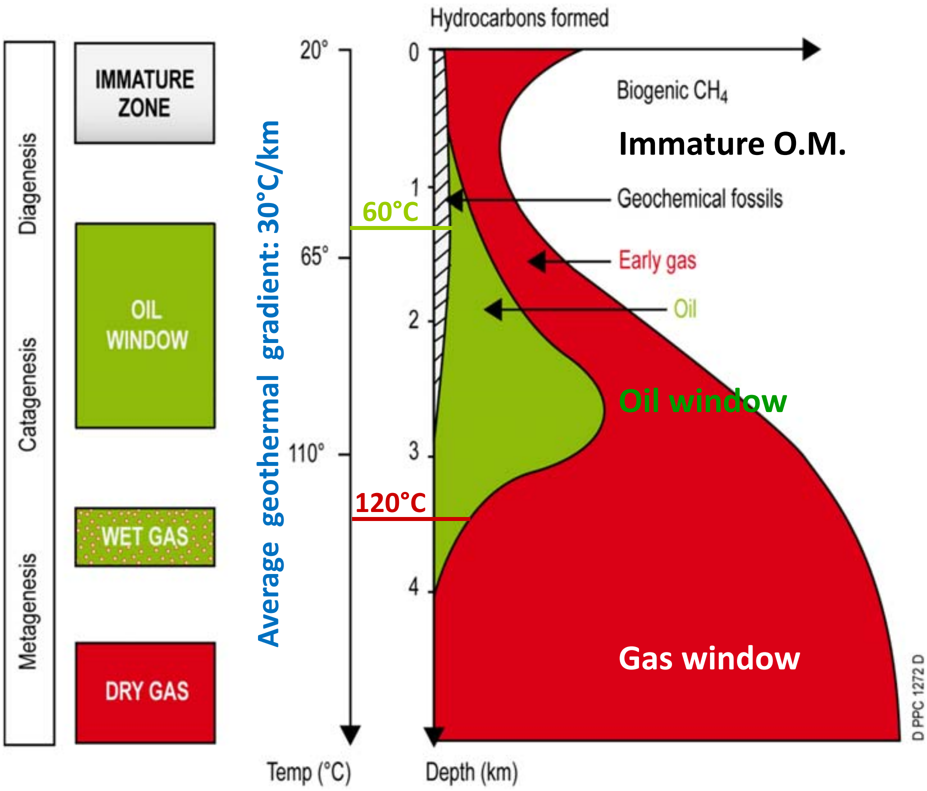
Animals = maximum 10% of total generated organic biomass

Transformation of O.M. & Kerogen

- **Diagenesis** [< 60°C]
  Bacterial degradation
  Immature stage

- **Catagenesis** [from 60 to 120°C]
  Thermal degradation
  → "weak" chemical bonds breaking
  Oil window

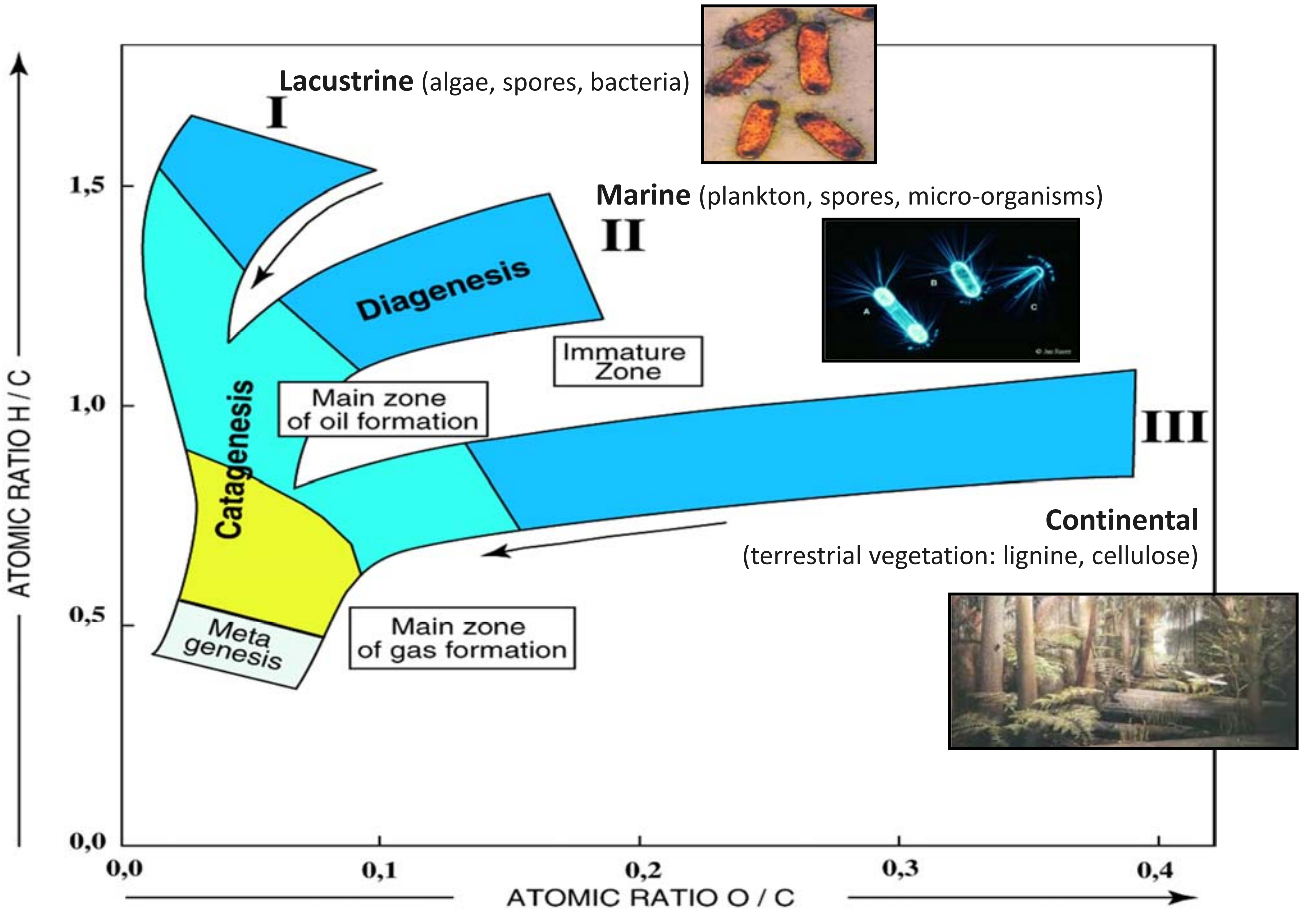
- **Metagenesis** [from 120 to 200°C]
  Thermal degradation
  → "strong" **C–C** bonds breaking (cracking)
  Gas window



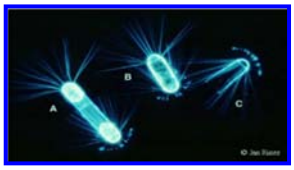
> 200°C : Metamorphism

Source rock maturation = chemical transformation mainly due to temperature increase during burial

Origin of kerogen: Van Krevelen diagram



Origin of hydrocarbons: summary



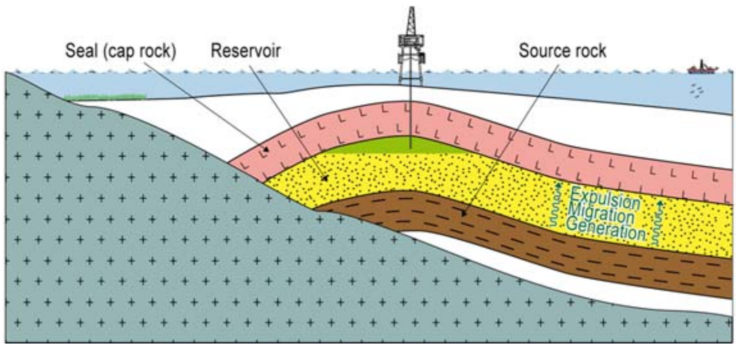
- **Three origins of OM > three different types of Kerogen**
  - Type I: lacustrine (lake algae, bacteria,…)
  - Type II: marine (zoo- & phyto-plankton, micro-organisms,…)
  - Type III: continental (terrestrial vegetation, forests, bacteria…)
- **Three steps of OM transformation within source rocks**
  - Diagenesis (burial, lithification)
  - Catagenesis (Kerogen transformation) → ~60°C…
  - Metagenesis (cooking, cracking) → ~120°C…
- **Three factors for OM maturation**
  - Temperature (sediments cooking, anoxic conditions, bacterial activity)
  - Pressure (sediment compaction, water expulsion)
  - Time (molecular evolution, new atomic combinations – compensates for low T°)

Petroleum systems

- Structure of hydrocarbons
- Origin and generation
- The Petroleum Trilogy
- Migration
- Traps

The Petroleum Trilogy

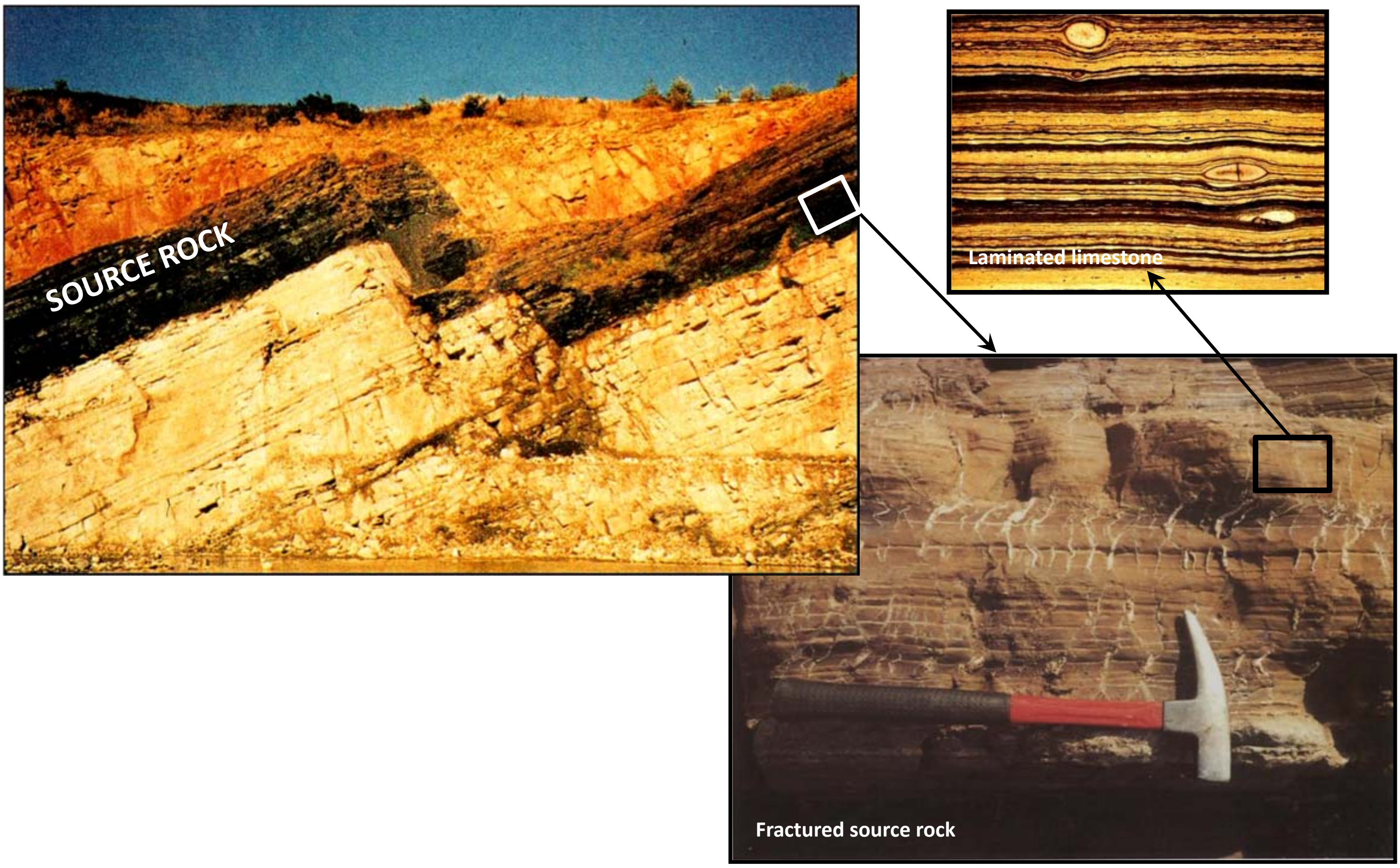
1. **Source rocks**
   - Hydrocarbons were generated from these rocks.
   - Usually, they are impermeable (e.g. shales).
   - They are rich in organic material.
   - Thin particles are mixed with organic matter.
2. **Reservoir rocks**
   - Hydrocarbons were accumulated in these rocks during geological times.
   - They are porous and permeable (e.g. carbonates or sandstones).
   - Porosity, permeability and water saturation characterize them.
3. **Seal rocks**
   - These rocks prevent hydrocarbons to migrate.
   - They are impermeable (e.g. shales, evaporites).
   - Thickness is a secondary parameters compared with large, continuous lateral extension.



1 - Source rocks

- **Definition**
  - Sedimentary rock rich in O.M. (ranging from 1 to 10%)
  - Mature enough to generate hydrocarbons (i.e. above 60°C)
- **Deposition**
  - Fine, muddy sediments deposited in quiet, low-energy, anoxic environments (lacustrine, lagoonal, open marine)
    - Lakes (algae, plankton)
    - Deltas (distal shaly facies)
    - Carbonate shelves (high organic production)
- **Lithology**
  - Very fine-grained rock (shales, mudstones, marls)
  - Interbedded laminations due to seasons
  - (sediment/O.M. > heterogeneity)
  - Low permeability → internal over-pressure → under-compaction
- **Process**
  - Preservation of organic matter
  - Generation of hydrocarbons
  - Expulsion of hydrocarbons

Examples of source rock outcrops

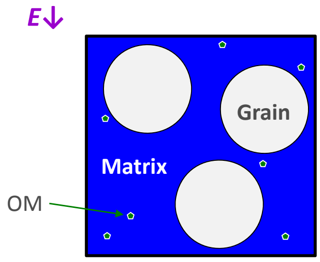


2 - Reservoir rocks

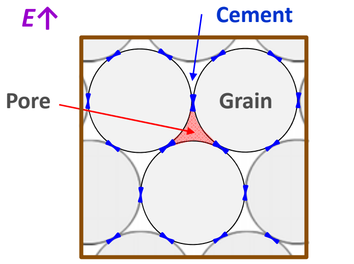
Reservoir rocks are porous and permeable (e.g. carbonates, sandstones).
Hydrocarbons were accumulated in reservoirs throughout geological time.
Porosity, permeability and water saturation are the parameters that characterize them.

- **Porosity: Φ**
- **Permeability: K**
- **Saturation: S**

The Reservoir Trilogy



Matrix ≈ 75%
Grain: 25%
Φ ≈ 0%, K ≈ 0



Grain ≈ 75%
Matrix ≈ Ɛ% (cement)
Φ ≈ 25%, K ↑

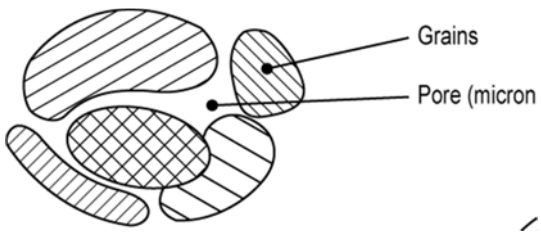
Two main types of reservoir rocks:

- Siliciclastic rocks (e.g.: sandstone)
  Produced mainly by physical processes (erosion, weathering). Source outside depositional area.
- Carbonate rocks (e.g.: limestone, dolomite)
  Produced mainly by chemical and bio-chemical processes, inside depositional area.

Porosity Φ

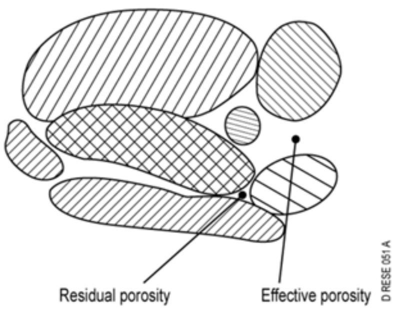
Porosity is defined as the ratio between the pore-space volume and the total volume of a rock sample (in %)

$$\text{Porosity} = \frac{\text{Volume of voids}}{\text{Total rock volume}} \times 100$$



In reservoir rocks, porosity usually ranges between 10% et 35 %.

- **Primary porosity**:
  Original intergranular porosity in sediment
- **Secondary porosity**:
  Due to diagenesis and fractures during and after lithification



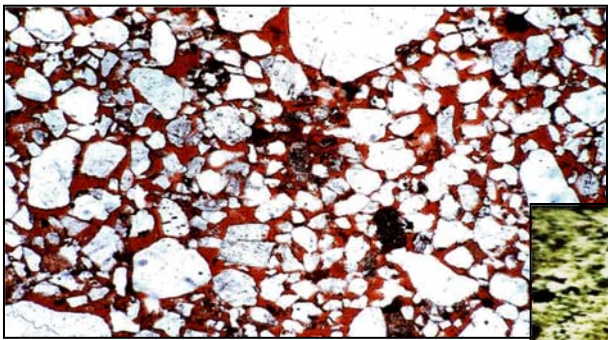
Only interconnecting voids are of any interest:
effective porosity
Non-connected voids define
residual porosity

Porosity values are measured on cores and extracted from logs

Porosity examples

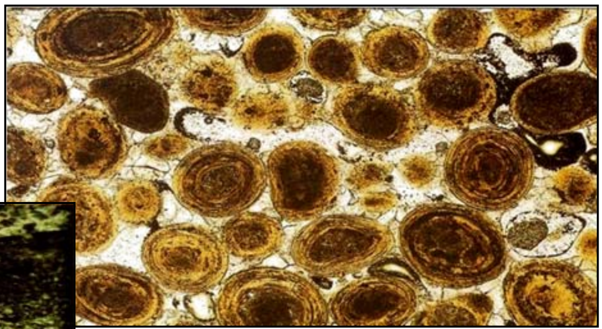
Thin sections

Sandstone

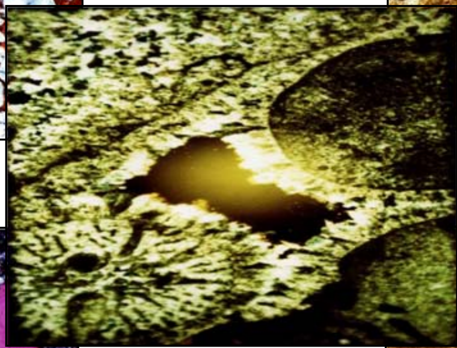


Porosity in red

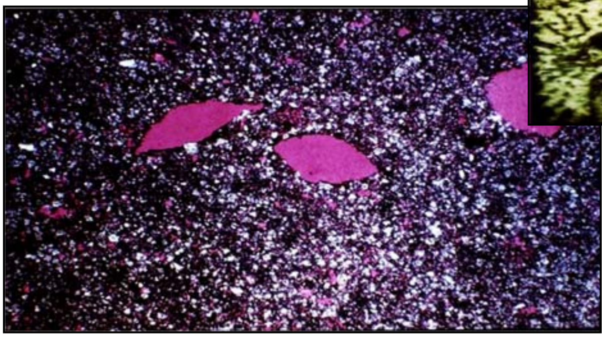
Oolithic limestone



Porosity in yellow

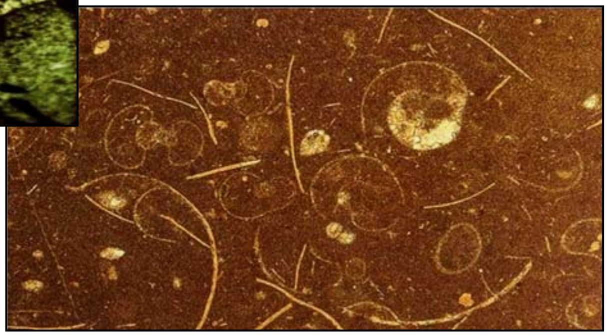


Sandstone with shells



Porosity in pink

Limestone with shells



Porosity in yellow

Permeability K

Permeability measures the ability of a rock to allow the displacement of fluids located inside the rock's porous network.

Commonly symbolized as K, in milliDarcy (mD), it is the key parameter to produce a reservoir.

Darcy's law

$$Q / A = (K / \mu) . (\Delta P / \Delta L)$$

Q : flow rate in cm^3/sec
K : permeability in Darcy
P : pressure, in atm
L : length, in cm

A : through surface , in cm^2
µ : fluid viscosity, in centipoise
K / µ : mobility

1 Darcy = $0{,}9869.10^{-12}$ m^2

High permeability values range between 10 mD and 1000 mD - or more for fractured reservoirs.

Within a rock, **permeability varies with direction** (horizontal ≠ vertical)

Permeability data come from core measurements and well tests

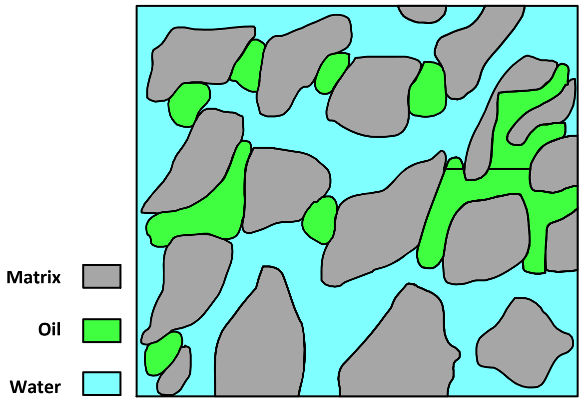
Saturation S

In reservoir studies, it is essential to know the type of fluid present in the pores.
Saturation for a given fluid is defined by the ratio of fluid volume vs pores volume, in %.

$$\text{Saturation} = \frac{\text{Fluid volume}}{\text{Pore volume}}$$

Fluids are mainly water but can also be oil and/or gas:

- Water saturation: $\mathbf{S_w}$
- Oil saturation: $\mathbf{S_o}$
- Gas saturation: $\mathbf{S_g}$



Thin section showing oil saturation

Saturation data come from well log interpretation and core analysis

Example of porosity and saturation

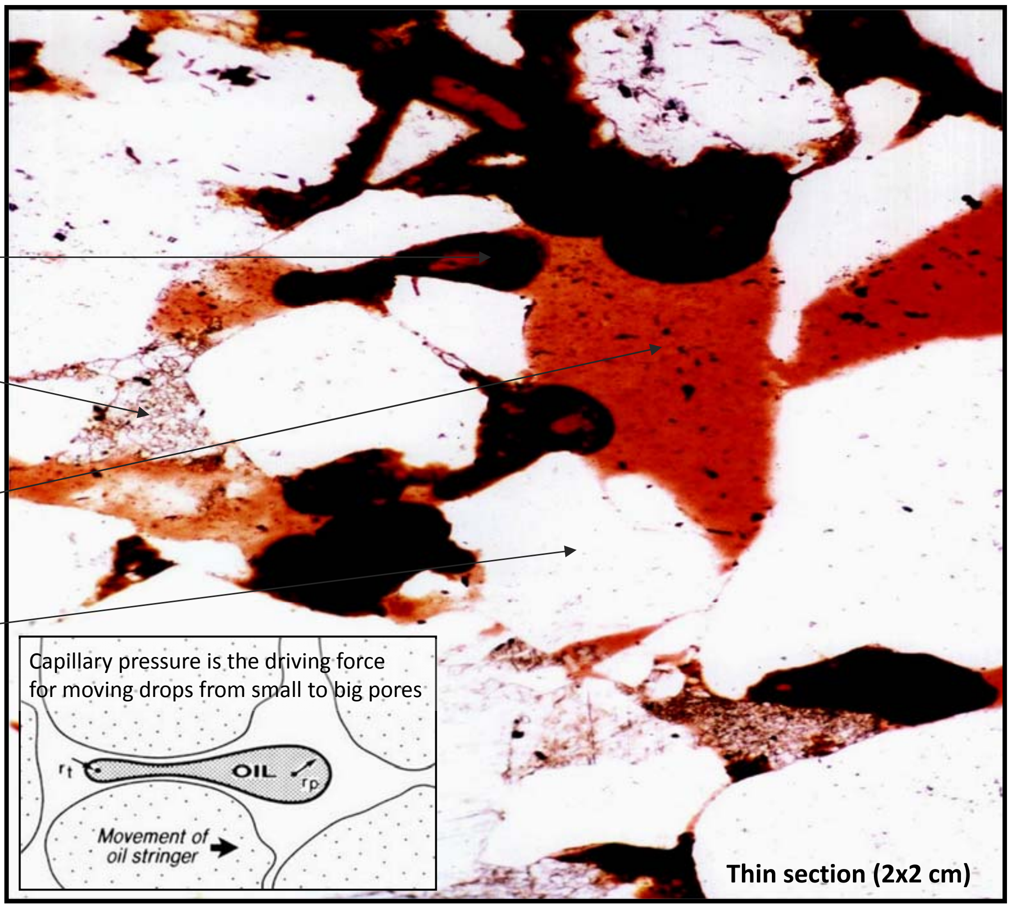
Oil-impregnated sand reservoir

Oil

Clay

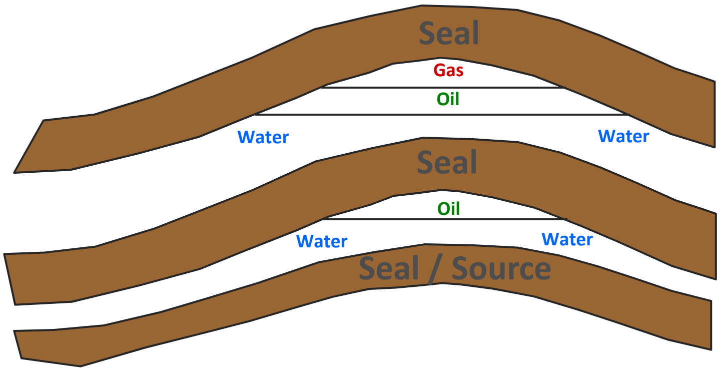
Water (red resin)

Grain (quartz)



3 - Seal rocks / Cap rocks

- **Non-permeable rocks, preventing hydrocarbons to further migrate**
- **Plastic rocks that can be deformed under stress/strain but not fractured**
- **Continuous lateral extension is a more critical parameters than thickness**
- **Most common lithologies:**
  - Shales
  - Saline rocks
  - Very compact sandstones or limestones (without porosity, i.e. “tight”)



The Petroleum Trilogy – Key points

	Source rock	Reservoir rock	Seal rock / Cap rock
Definition	• Sedimentary rocks rich in OM, mature enough to generate hydrocarbons	• Porous and permeable rocks • Allow displacement and hydrocarbon accumulation	• Non-permeable rocks (prevent hydrocarbons from migration) • Plastic rocks (can be deformed but not fractured)
Lithology	• Very fine-grained rocks (shales, mudstones, marls,…) with interbedded laminations (sediment/OM) • Low permeability (internal over-pressure > under-compaction)	• Clastic rocks (e.g. sandstone) • Carbonate rocks (e.g. limestone)	• Shales or salt rocks (plastic rocks) • Very compact sandstones or limestones (without porosity, “tight”)
Specificity (process, parameters,…)	• OM production, deposition, preservation & maturation • HC generation, expulsion & migration	Petrophysical parameters: • Porosity: Φ • Permeability: K • Saturation: S	• Lateral extension and layer continuity are more important than thickness

Petroleum systems

- Structure of hydrocarbons
- Origin and generation
- The Petroleum Trilogy
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- Traps

Hydrocarbon migration

Types of migration

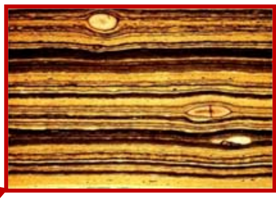
The word "migration" covers all types of displacements of hydrocarbons, from the source rock where they originated to the trap where they accumulate.

Primary migration
Expulsion of hydrocarbons from the source rock either towards a porous & permeable adjacent rock or via a permeable fault. This migration takes place over very short distances (a few cm) and is controlled by pressure (higher in source rock), temperature and expelled molecules diameter.

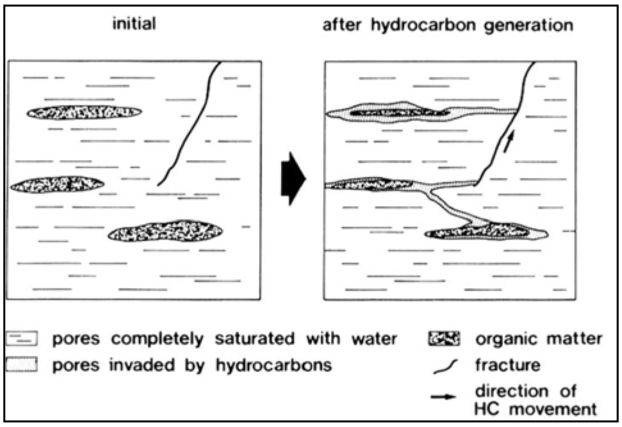
Secondary migration
Displacement of hydrocarbons (after expulsion from the source-rock) over distances ranging from a few meters to several hundred of kilometers, until they are trapped.
This migration takes place inside a reservoir/carrier rock or along a non-sealing fault.
Migration pathways are complex and specific to each basin. Migration can be lateral and/or vertical (both upward or downward).

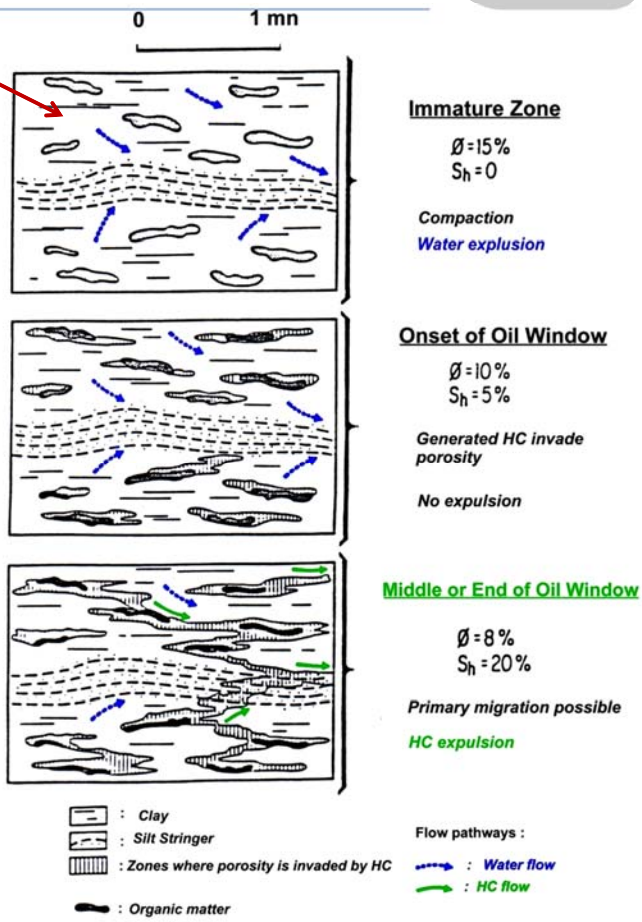
Dysmigration
Hydrocarbon displacement from a "leaking" reservoir to the surface (i.e. seepage).

Expulsion / primary migration



Internal over pressure
when available pore
volume (~30%)
is filled up

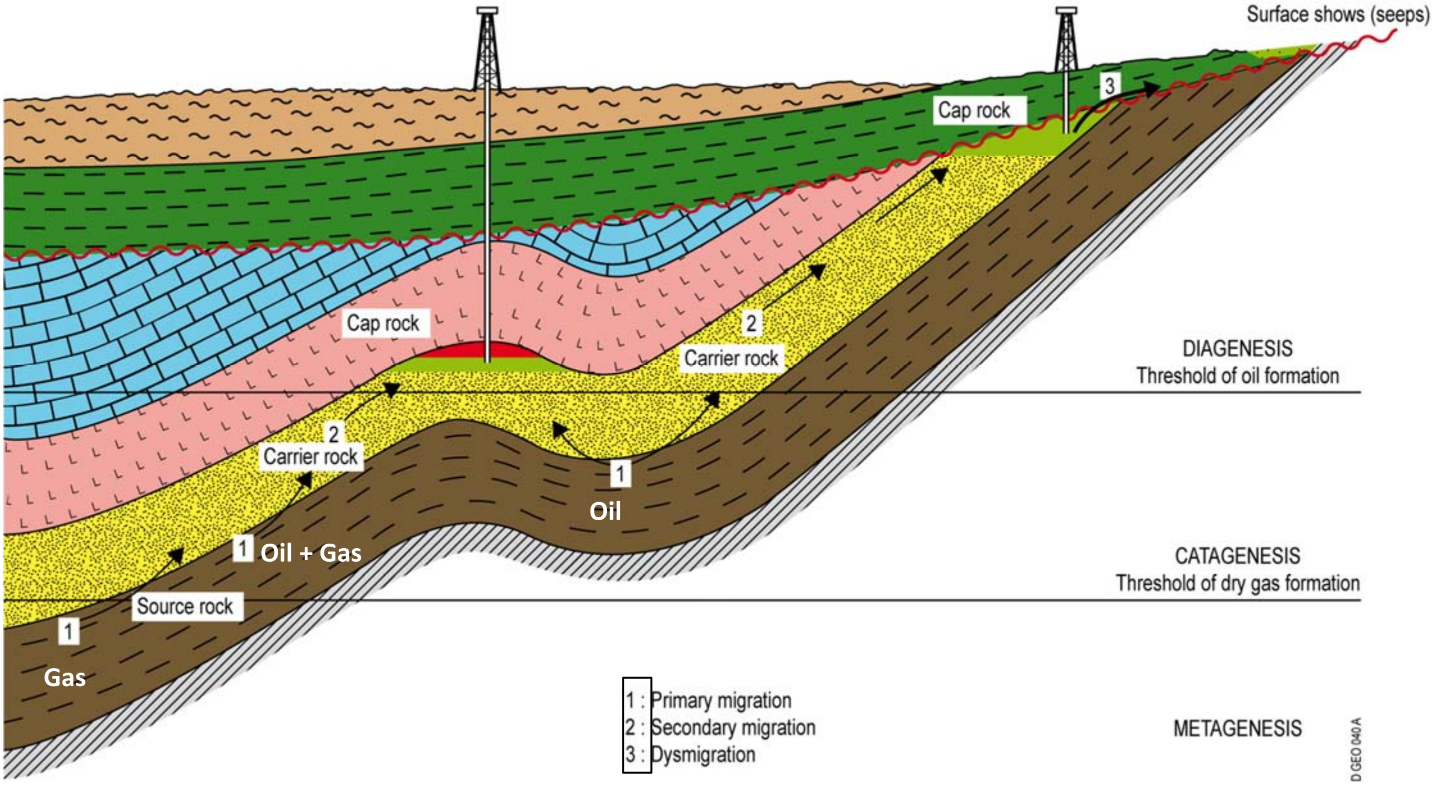




Secondary migration

- **Migration happens only in reservoir (carrier) rocks or along (non-sealing) faults**
- **Transportation occurs from high to low pressures:**
  - Importance reservoir rock petrophysical characteristics
    - Porosity, permeability, capillary pressure
  - Influence of water drive (active aquifer)
    - Migration velocity
    - Accumulation distribution

Hydrocarbon migration



Migration happens only in reservoir rocks or along faults

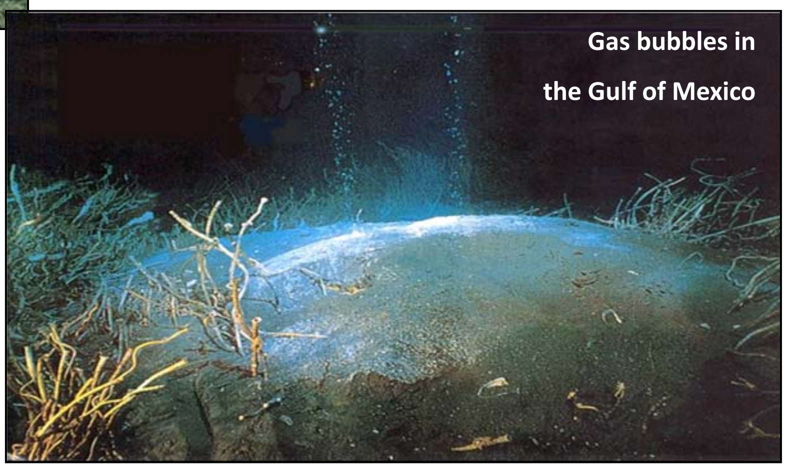
Transport occurs in carrier rocks from high to low pressures

→ importance reservoir rock petrophysical characteristics (Φ, K, Pc)

Dysmigration: seeps and surface shows

On land…

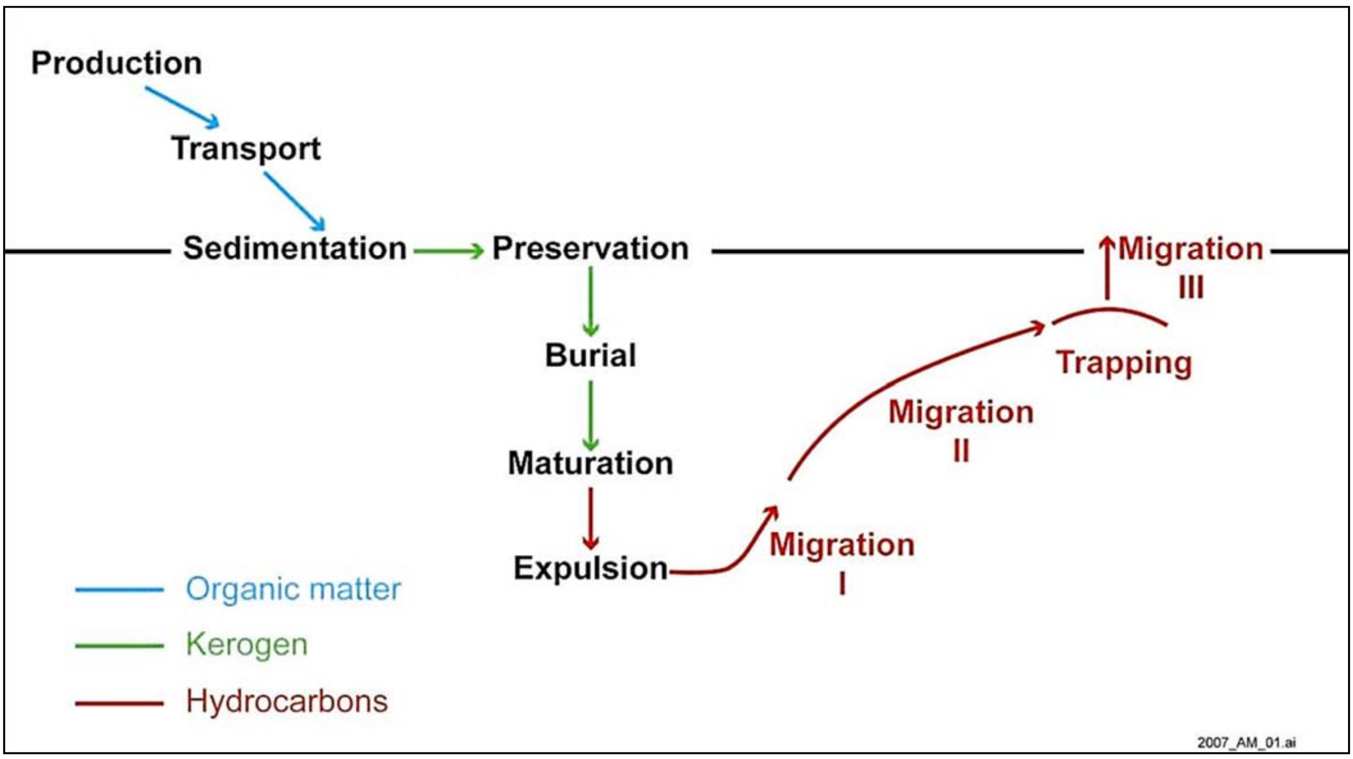
…and in the sea.



Hydrocarbon migration: summary

- **Compaction of sediments (burial, diagenesis)**
  - Temperature increase - Porosity decrease - Fluid expulsion
  - Transformation of O.M. into kerogen (thermal windows depths [oil, gas] depend on geothermal gradient in basin)
- **Expulsion of hydrocarbons from source rock**
  - Volume of generated HC reaches critical threshold: creation of micro-fractures by internal over pressure
  - Expulsion controlled by pressure gradient (from high to low pressure) between two adjacent rocks (with ≠ lithologies) or along a permeable fault
  - Independent from relative position (ascending or descending)
- **Migration of hydrocarbons within reservoir rocks**
  - Primary migration (expulsion)
  - Secondary migration (towards accumulation) - Driven by high-to-low pressure gradient - Occurs only in reservoir formations (i.e. porous and permeable rocks) via pores, fractures or heterogeneities - Blocked by permeability barriers (seals > entrapment)
  - Dysmigration (leak > seeps)

Organic matter - Kerogen - Hydrocarbons – Key points



Petroleum systems

- Structure of hydrocarbons
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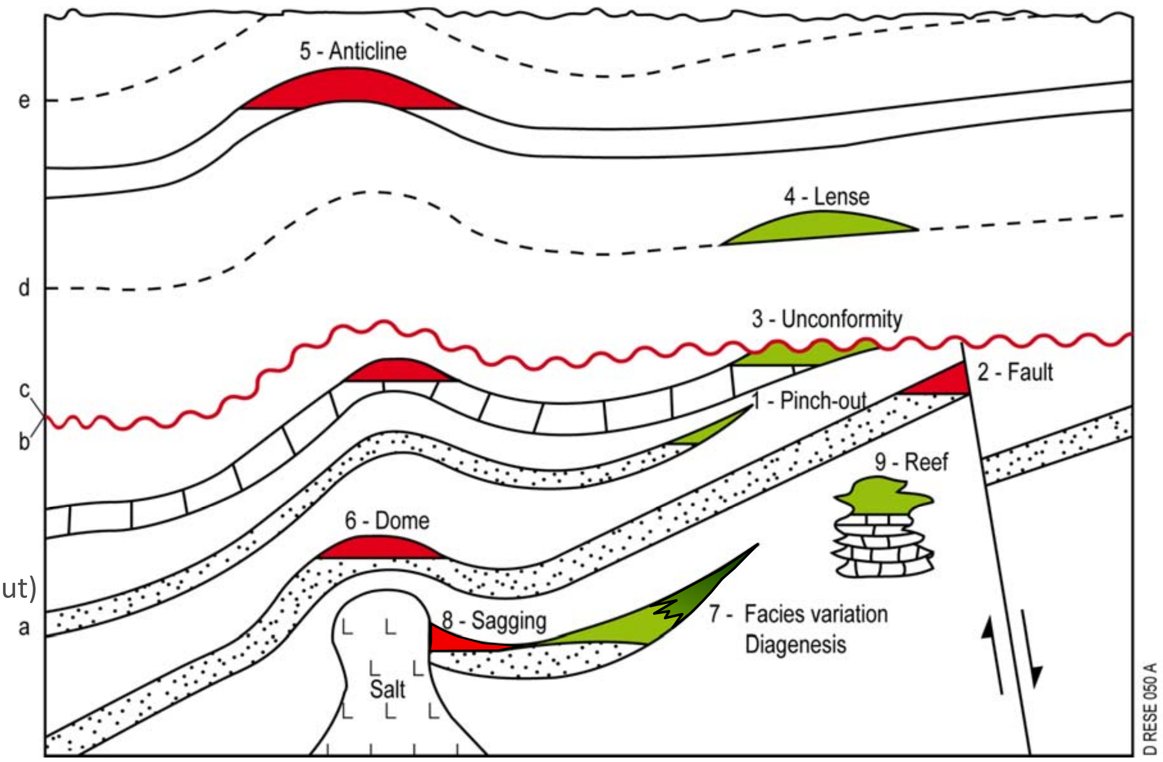
Main types of traps

Trap = geological anomaly

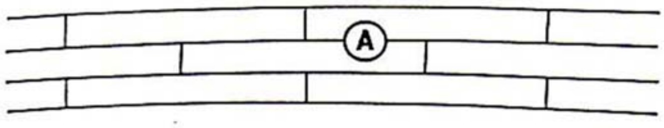
(either Tectonic/structural or Stratigraphic/lithological)

- **Structural traps:**
  - Anticline
  - Fault
  - Salt dome
  - Salt sagging
- **Stratigraphic traps:**
  - Facies variation
  - Diagenesis
  - Reef
  - Lense
  - Wedge (pinch-out)
  - **Unconformity** *(mixed)*

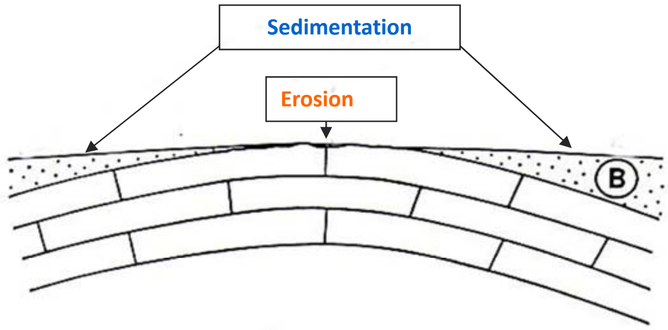


Unconformity

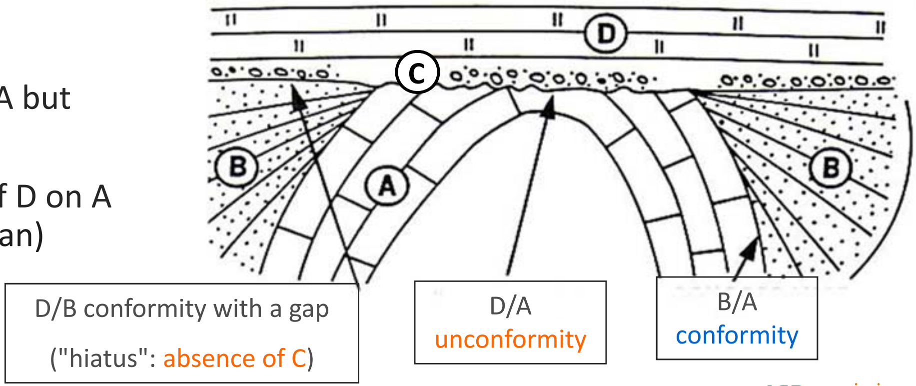
- Deposition of layer **A**



- Deformation of layer **A** (compression)
- Erosion of **A** and sedimentation of **B** ("syntectonic" deposition of **B** – i.e. during deformation)



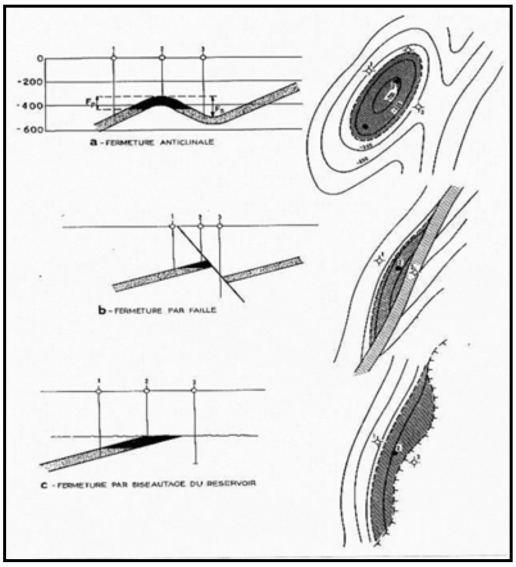
- Final stage
  - C lies unconformably on A but conformably on B
  - progressive conformity of D on A via C and B (syntectonic fan)



Example of trap analog: unconformity

Hydrocarbon trap and entrapment

- **Trap definition**
  - A trap always involves the Reservoir/Seal couple
  - The structural closure: corresponds to the maximum extension of hydrocarbons filling (both vertical & horizontal boundaries – e.g. spill point, sealing fault, wedge,…)
- **Entrapment process**
  - Migration pathways go from high to low pressures, within porous and permeable carriers rocks (i.e. potential reservoirs). Migration stops due to permeability barriers (sealing faults, diagenetic tightness,…).
  - Cap rocks (seals) prevent hydrocarbon from further migration and leaking (dysmigration).
  - An adequate timing between trap formation and hydrocarbon migration (“Play”) is required

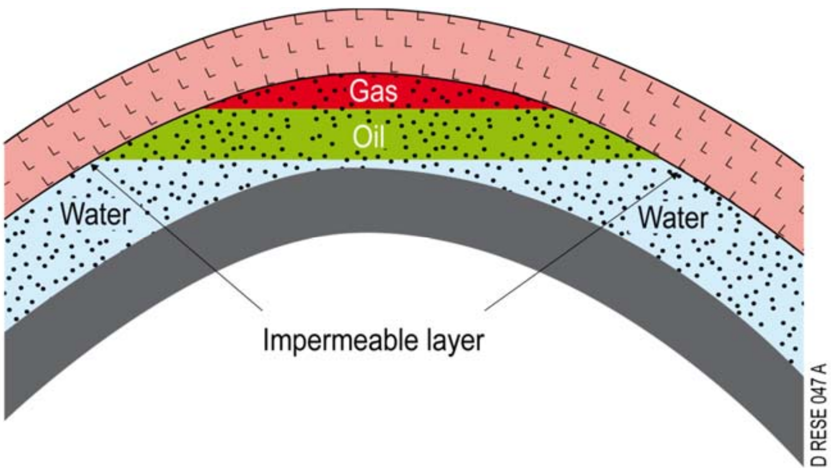


Hydrocarbon traps: summary

A field is a closed zone made of a porous and permeable reservoir rock containing hydrocarbons (oil and/or gas) and residual water.

It is covered by a seal (cap-rock) thus forming a trap.

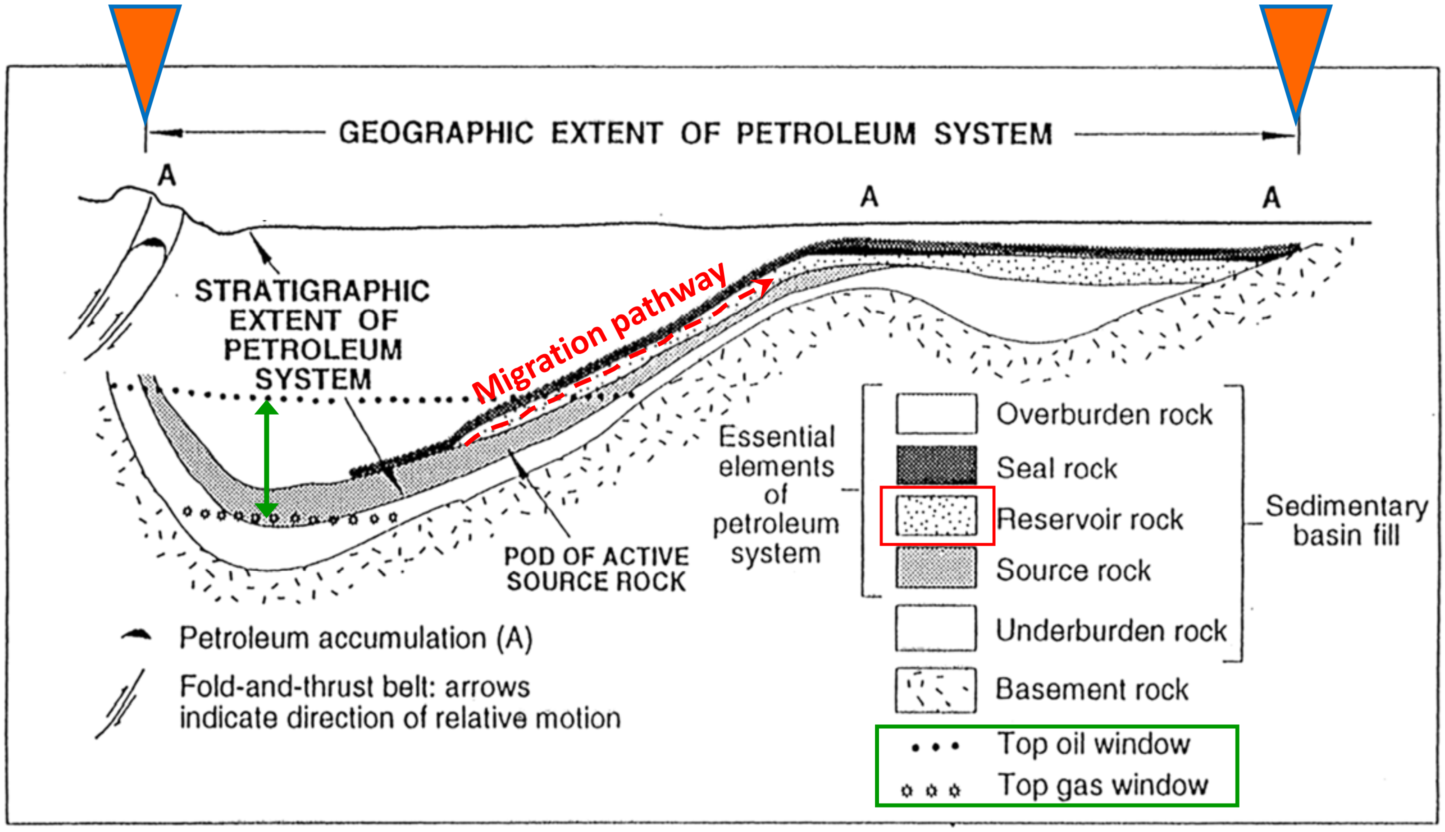
The hydrocarbon zone can be in communication with an aquifer.



The main objectives of reservoir studies are: development optimization, optimal well location and production forecast.

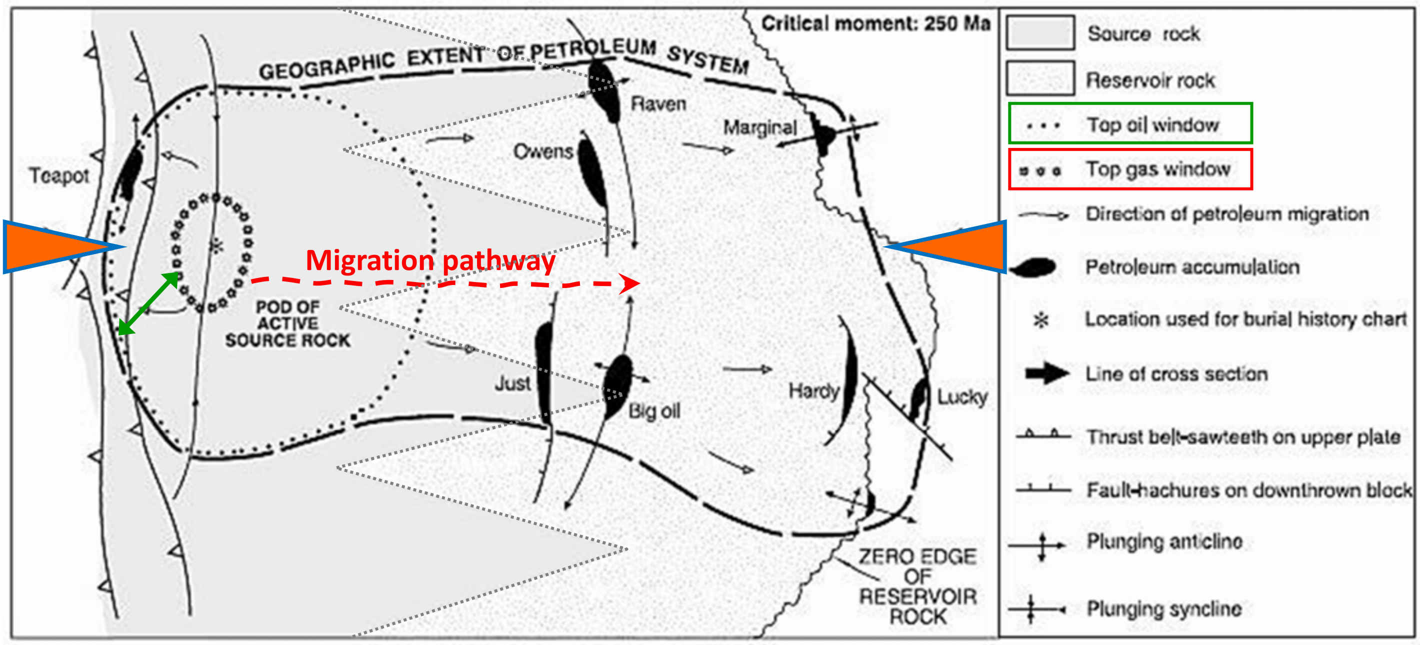
The life for a producing field varies from a few years to more than 20 or 30 years.

Cross-section of a petroleum system



From Magoon&Beaumont – AAPG

Map of a petroleum system



From Magoon&Beaumont – AAPG

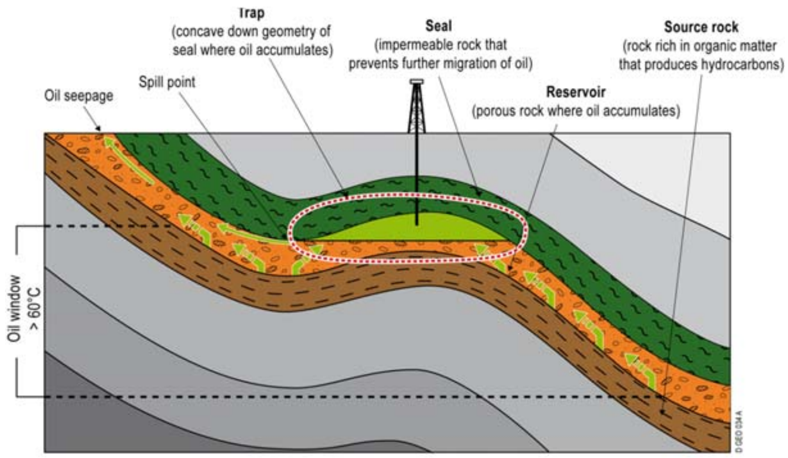
Petroleum systems - Key points

Conditions for hydrocarbon field formation

Necessary existence of:

- **one** (or more) **mature source rock,**
- **one** (or more) **reservoir rock,**
- **one seal rock,**
- **a phase of migration** (and pathways),
- **one** (or several) **traps,**

…and:



- an adequate **timing** between trap formation, hydrocarbon generation and migration
- sufficient **quantities** of generated hydrocarbons to feed the trap
- preservation of trap **integrity** throughout geologic times

Timing between elements and processes

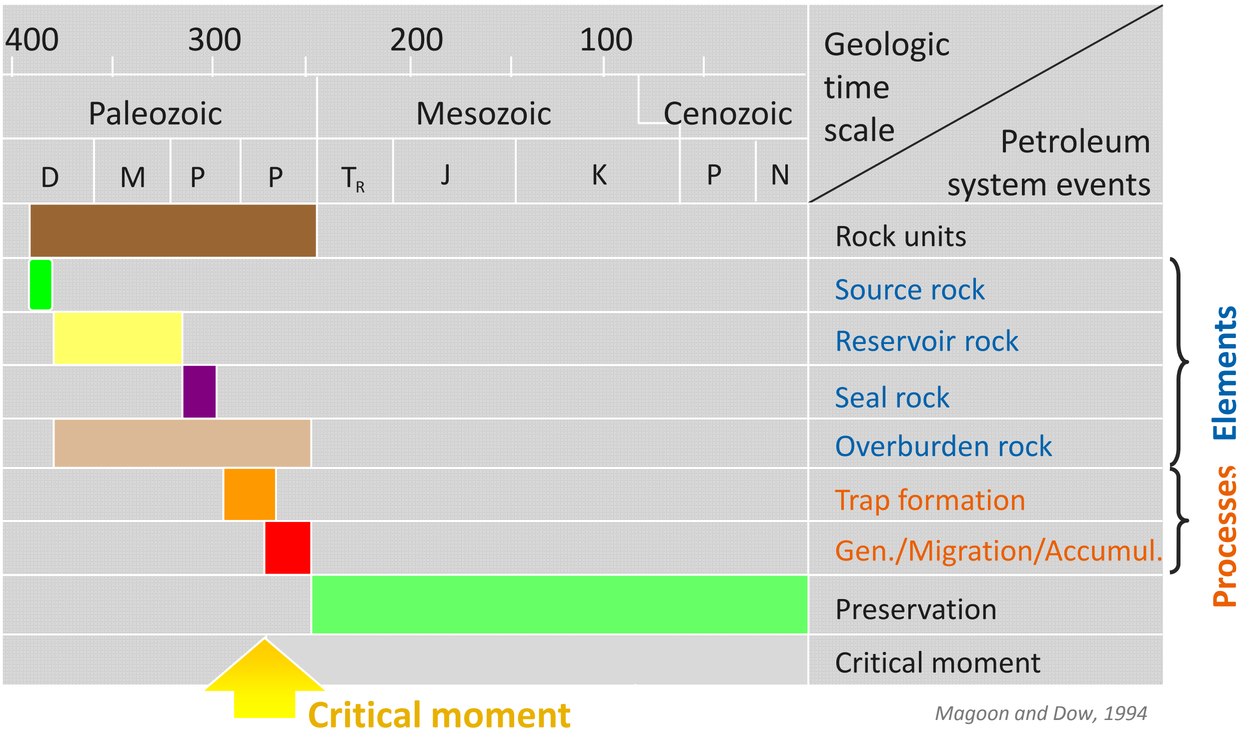
The trap must be available before/during migration

Trap

2. Processes: Generation → Migration → Accumulation and preservation

1. Elements: Source rock | Migration pathways | Reservoir and seal

Petroleum system: Chart of events



Magoon and Dow, 1994

Time of expulsion and migration
(traps need to already exist)

Exploration tools & techniques

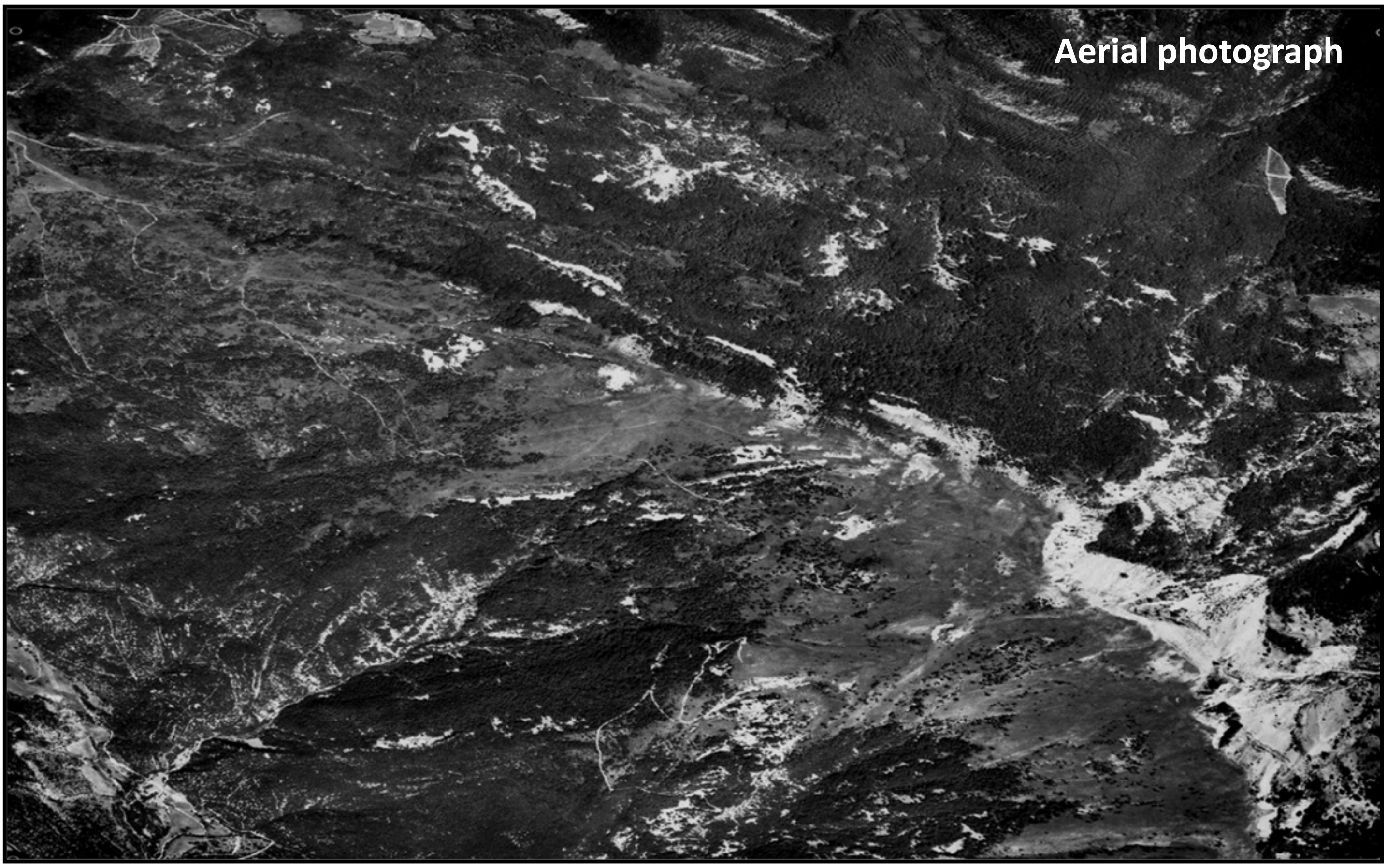
Exploration tools & techniques

IV

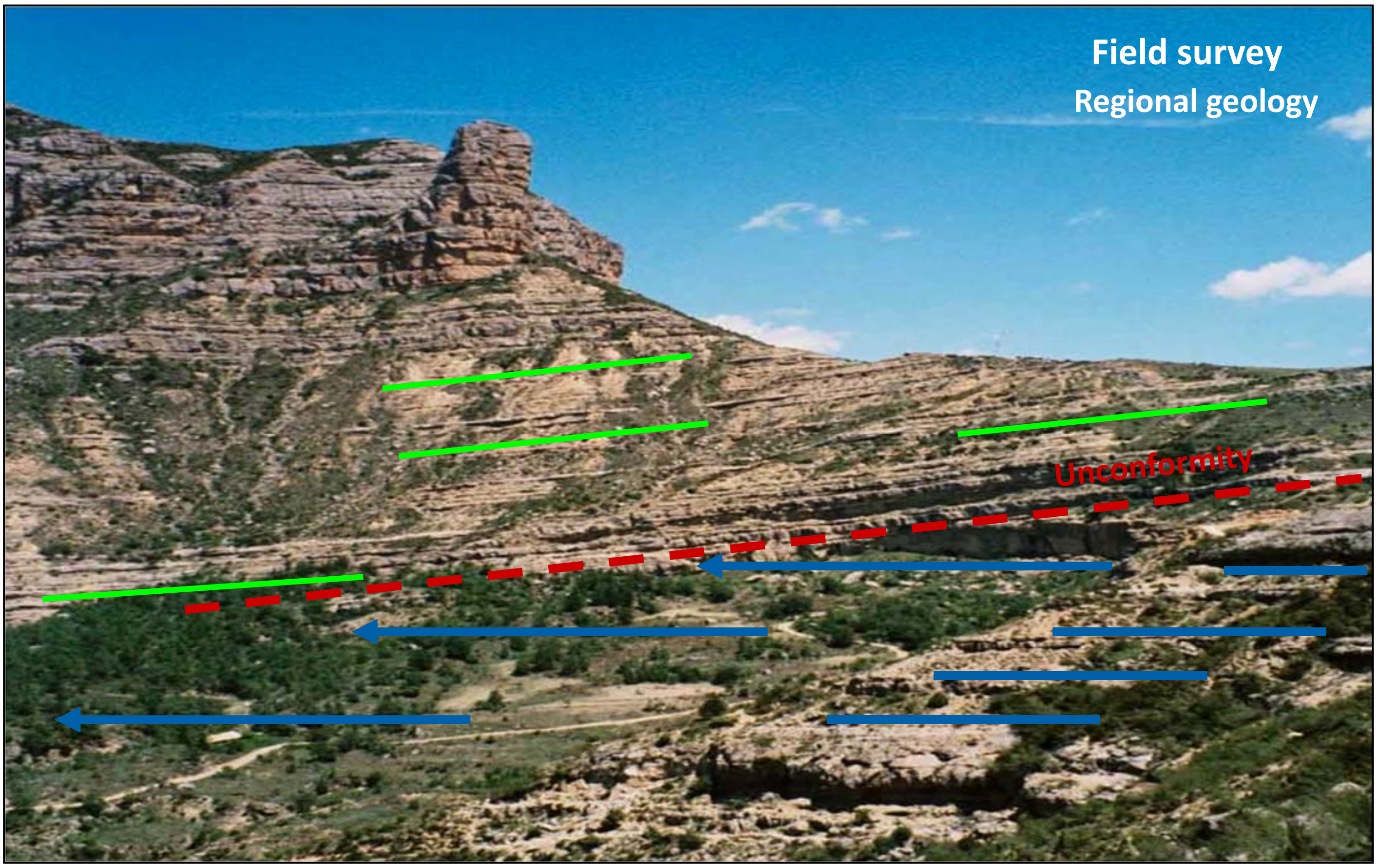
- Exploration geology
- Petroleum geophysics
- Operations geology

Preliminary geological survey

Preliminary geological survey

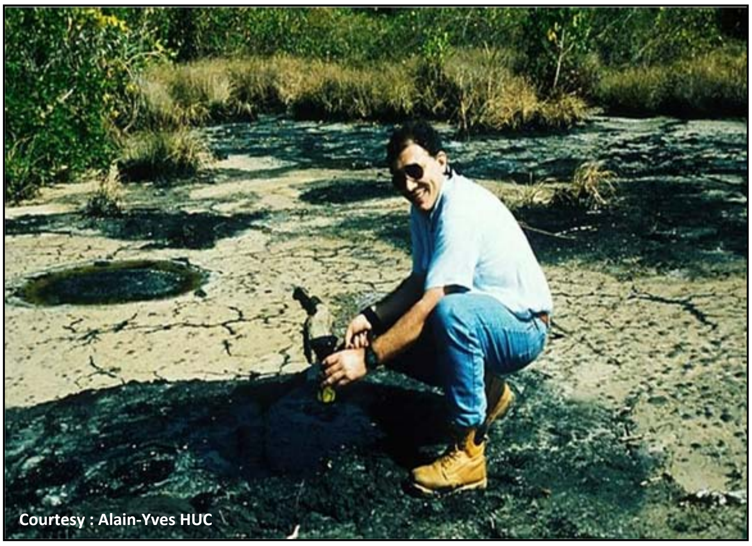


Preliminary geological survey



Preliminary geological survey

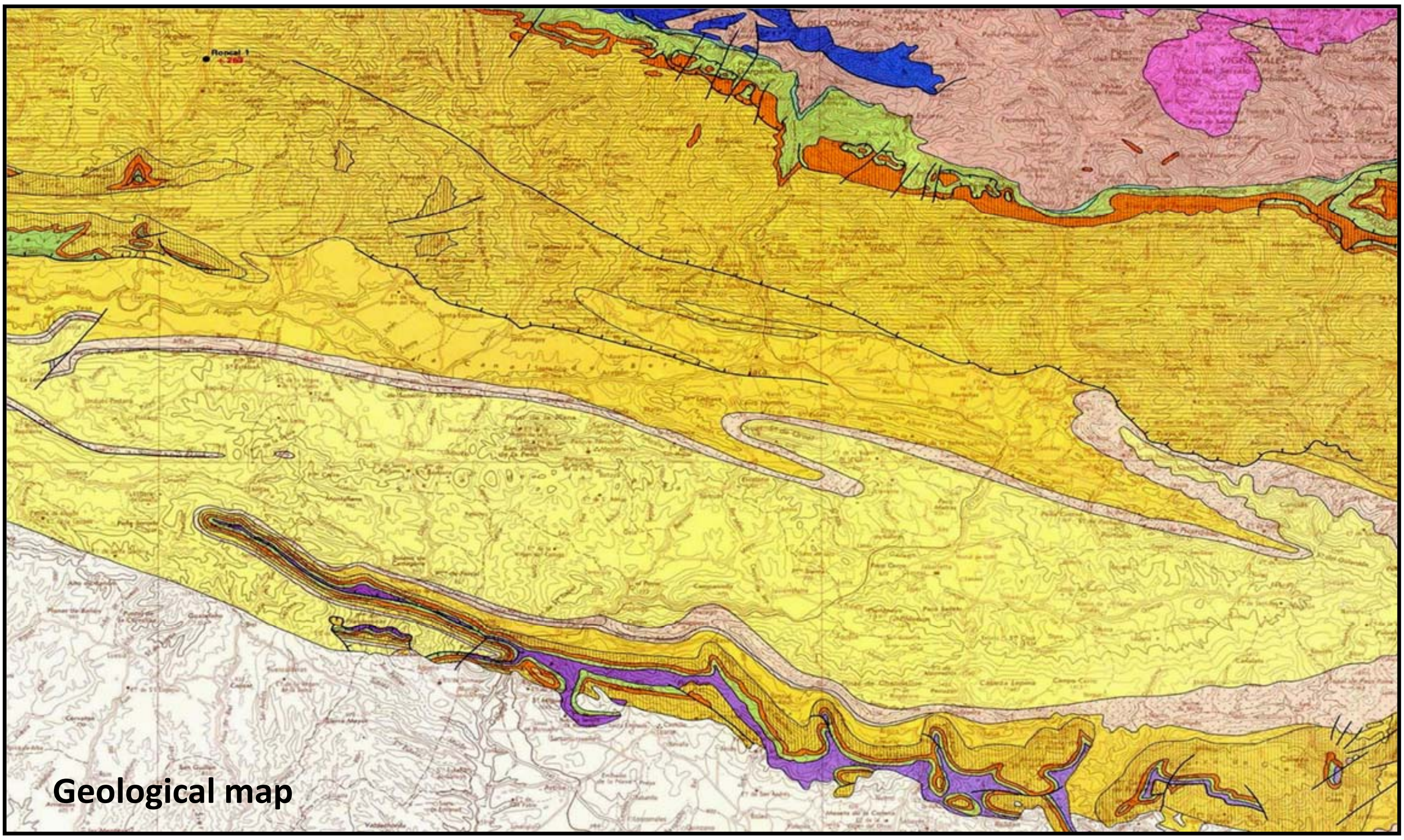
Preliminary geological survey


Courtesy : Alain-Yves HUC

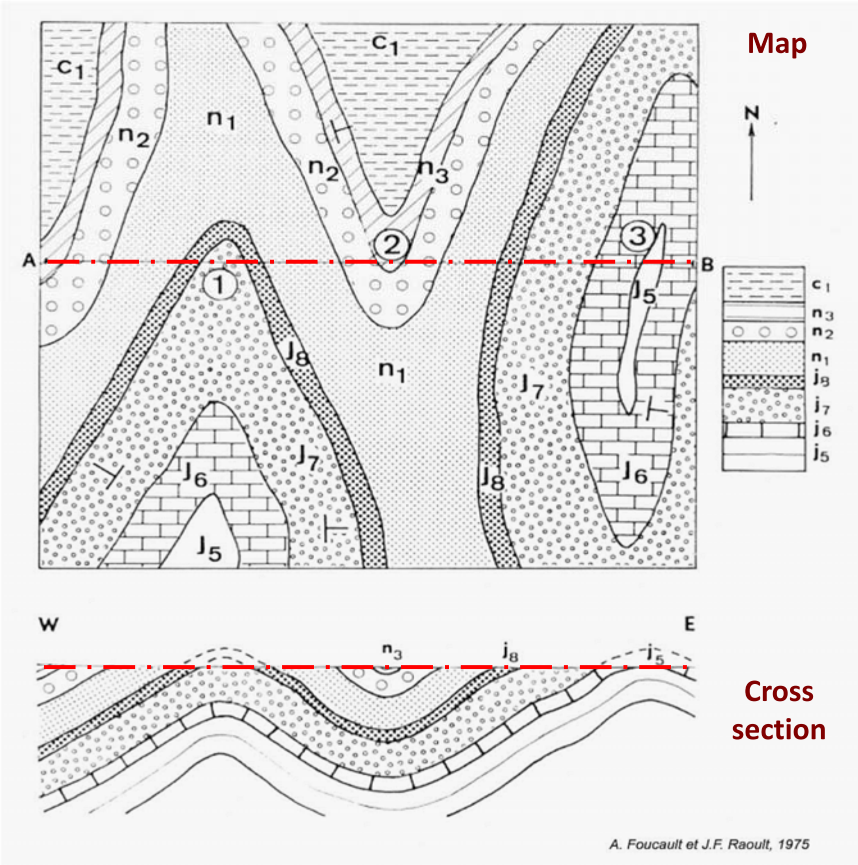
Oil seeps

Evidence at surface

Preliminary geological survey


Geological map

Preliminary geological survey



Aspect des plis sur une carte géologique.

Structural interpretation from a geological map

Exploration tools & techniques

- **Petroleum geophysics**
  - Introduction to petroleum geophysics
  - Principles of seismic reflection
  - Seismic acquisition
    - Land seismic
    - Marine seismic
  - Seismic processing and imaging
  - Seismic interpretation
  - Seismic attributes and facies
  - 4D seismic

Geophysics in E&P

- **The science of geophysics analyzes the Earth via quantitative physical methods**
- **Geophysical methods apprehend physical rock parameters - or rather: their contrasts and variations in space**
- **Geophysical methods analyze either artificial signals or natural signals/phenomena**
- **Geophysical methods can be applied on land or offshore, two or three dimensions, on ground surface or in wells**
- **Due to significant depths of investigation, the number of petroleum geophysical methods is limited, compared to other geophysical methods (e.g. applied to mining)**
- **The main geophysical method applied to petroleum is seismic reflection, mainly 3D seismic method (3 dimensions)**
- **Seismic reflection is often used in combination with seismic refraction or potential methods (e.g. gravimetry and magnetometry)**

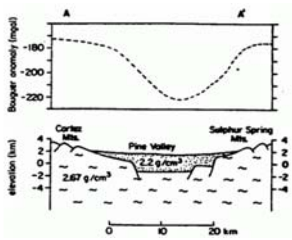
Petroleum geophysical methods

Natural methods	Artificial methods	Interpreted Features
Gravimetry		Salt, Shale, Granite
Magnetometry		Basement
	Reflection seismic	Sedimentary contrasts
	Refraction seismic	Basement
	Electric	Granitic basement
Magneto-Telluric		Shallow formations

Non-seismic methods

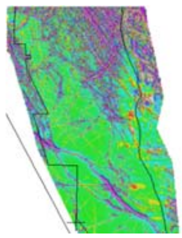
Three main types of tools:

- **Gravity/Gradiometry** = Density



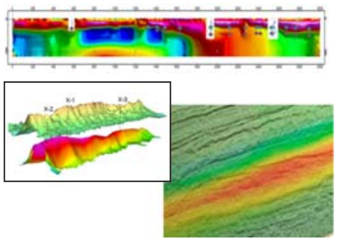
Basins, basement, closures

- **Magnetometry** = Susceptibility



Dykes, basement, de-risk intrusive

- **Electro-magnetism** = Resistivity



Near-surface and deep structure or fluids

Exploration tools & techniques

- **Petroleum geophysics**
  - Introduction to petroleum geophysics
  - Principles of seismic reflection
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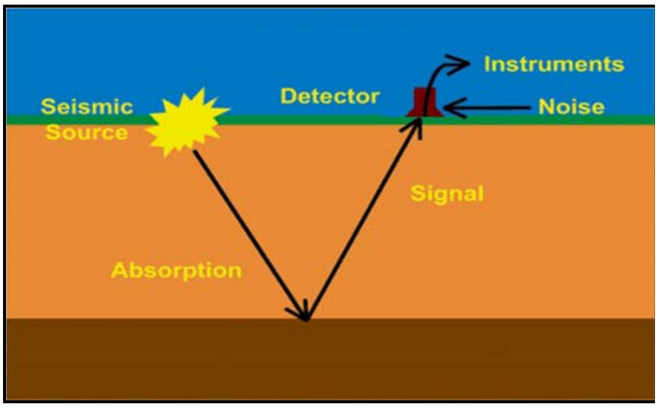
    - Land seismic
    - Marine seismic
  - Seismic processing and imaging
  - Seismic interpretation
  - Seismic attributes and facies
  - 4D seismic

Petroleum geophysics

General principle of seismic reflection

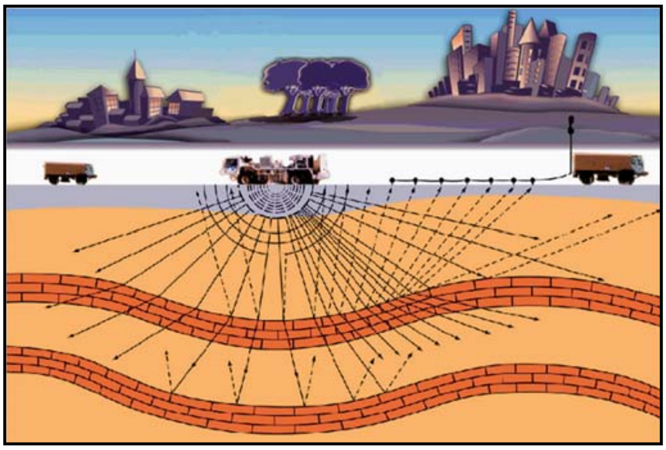
- **Scanning subsurface**
  - Generation of an acoustic wave front
  - Interaction with layers interfaces
- **Interfaces**
  - Modification of wave propagation
  - Reflection, Transmission, Refraction
- **Part of the energy is reflected back to the surface and recorded at surface with a system of receivers**



- **Seismic reflection is a very powerful tool, with a significant depth of investigation (down to 15.000m) and potential high resolution (e.g. vertical accuracy, that varies from 20m to 2m)**

2D land reflection seismic principle

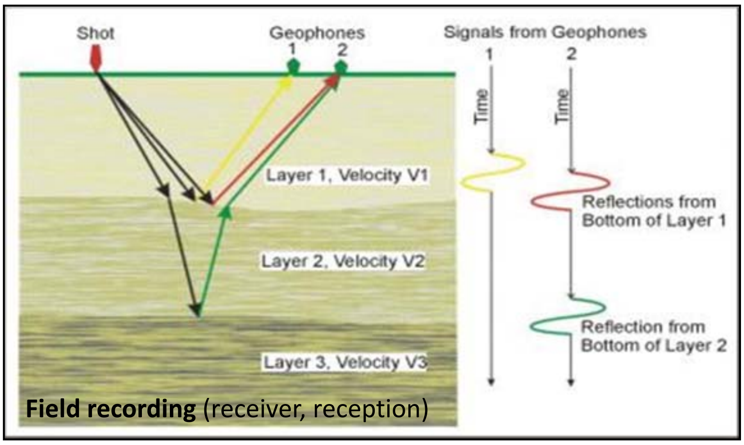
- **Field set-up and geometry:**
  - Sources (land and marine)
  - Receivers (geophones, hydrophones)
  - Recording lab (truck, vessel)
- **Improvement of Signal/Noise ratio (i.e. geological response vs interferences)**



Emission
Source: Vibrator

Reception
Receivers: Geophones

Recording Truck



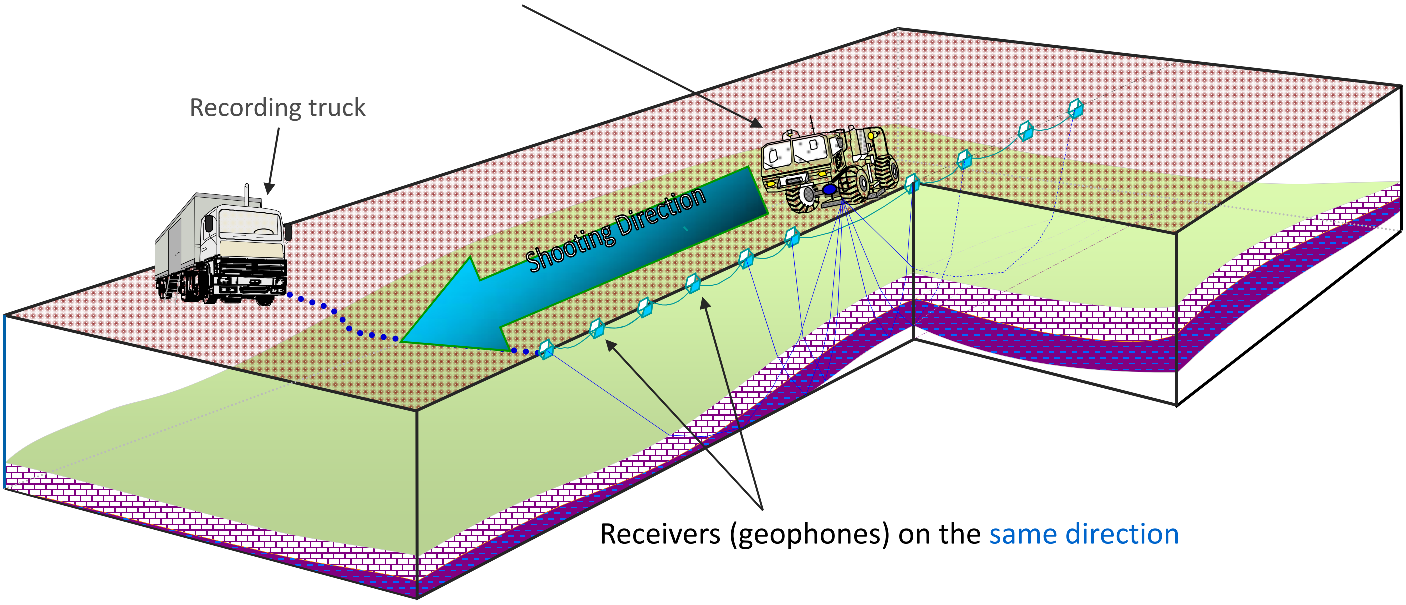
Field recording (receiver, reception)

Principle of 2D reflection seismic: land

2D land acquisition

Seismic source (vibro truck) moving along one direction

Recording truck

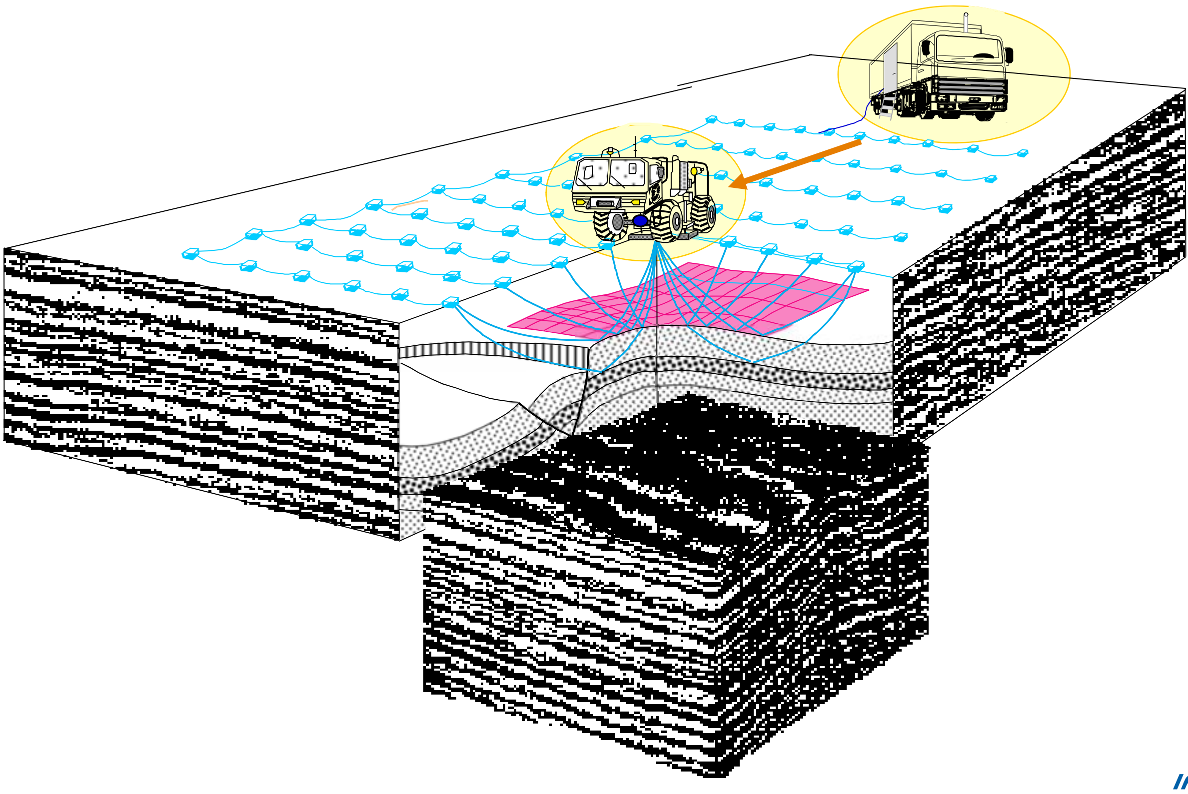


Receivers (geophones) on the same direction

Shooting direction = Receiving direction = Seismic line or profile
(after processing = Seismic section)

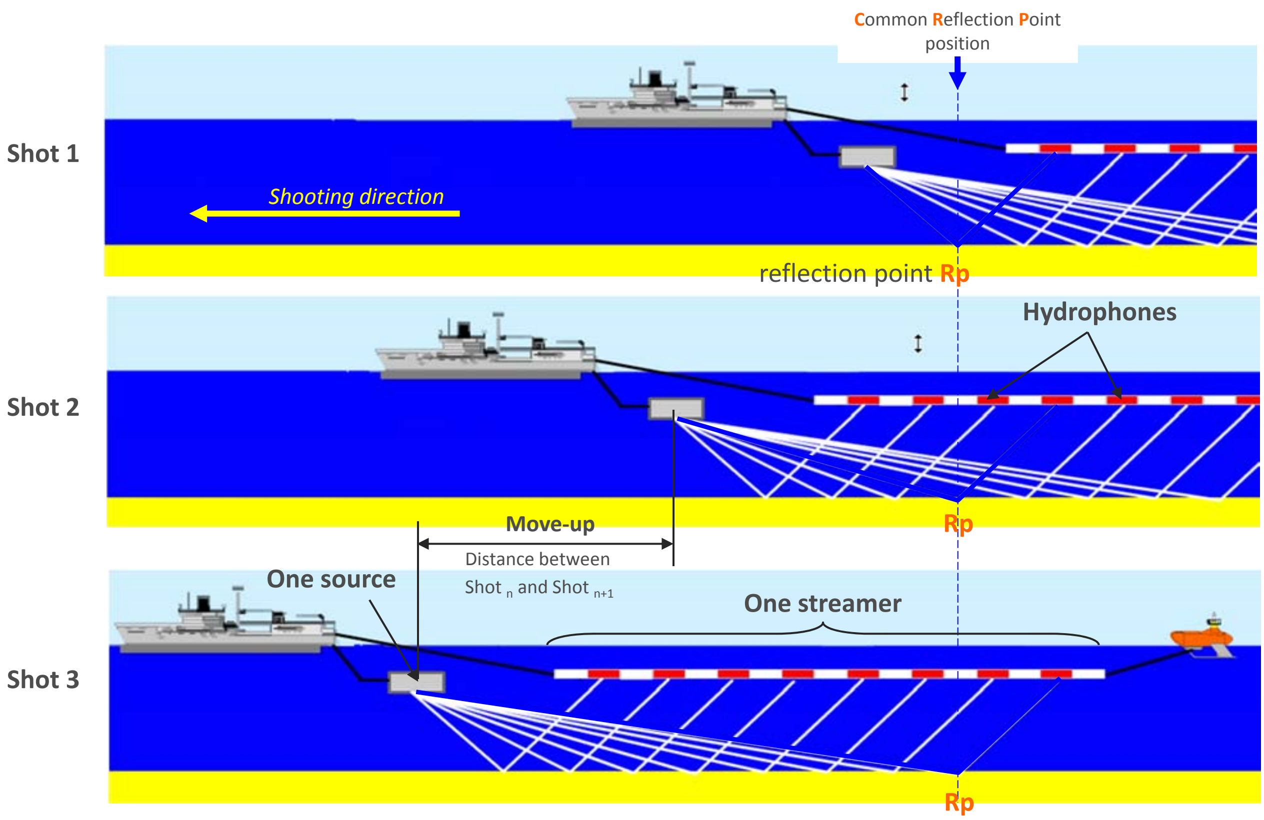
Principle of 3D reflection seismic: land

3D land acquisition



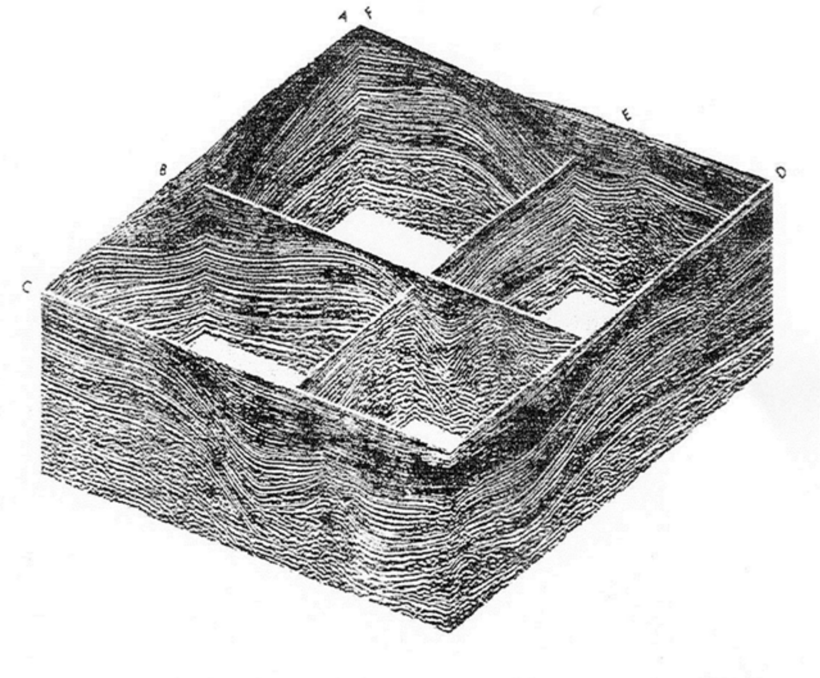
Principle of 2D/3D reflection seismic: marine

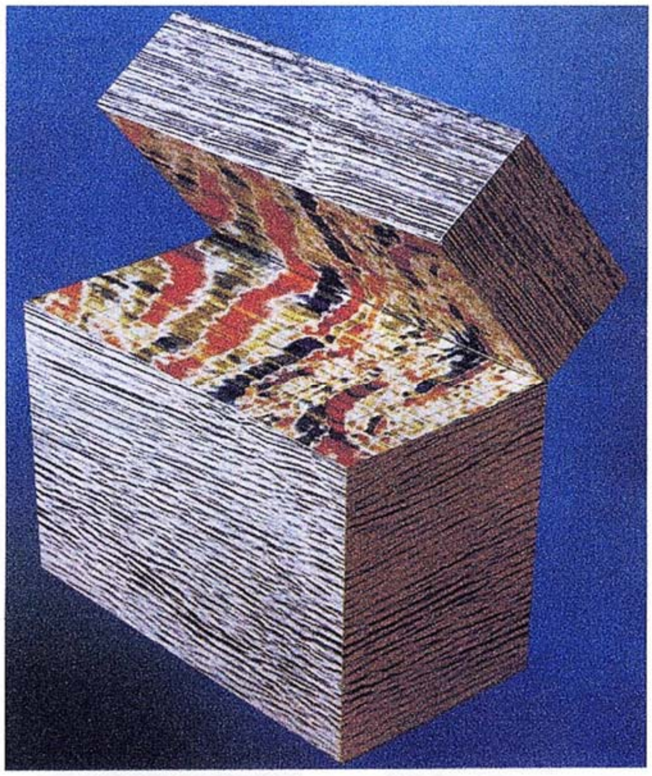
2D/3D marine acquisition



Processed seismic data

2D seismic grid (mesh) vs **3D seismic block** (cube)





Acquisition - Processing - Interpretation

- **Data Acquisition**
  - Instantaneous measurement
  - Time recording
  - Emission – Reception - Recording
- **Data Processing**
  - Field processing
  - Processing center
  - Processing steps (Quality Control, Editing, Correction, Filtering, Pre-processing, Processing, Migration, Inversion, …)
- **Data Interpretation**
  - Structural and/or Stratigraphic model
  - Prospect definition

Seismic waves propagation: definitions

Within an elastic and isotropic solid

Volume waves

- **Compressional waves "P waves":** → **propagation into solids and liquids**

  Also called: primary wave, longitudinal wave, pressure wave, dilatational wave, non-rotational wave

- **Shear waves "S waves":** → **propagation only into solids**
  → **polarization into SV-wave and SH-wave**

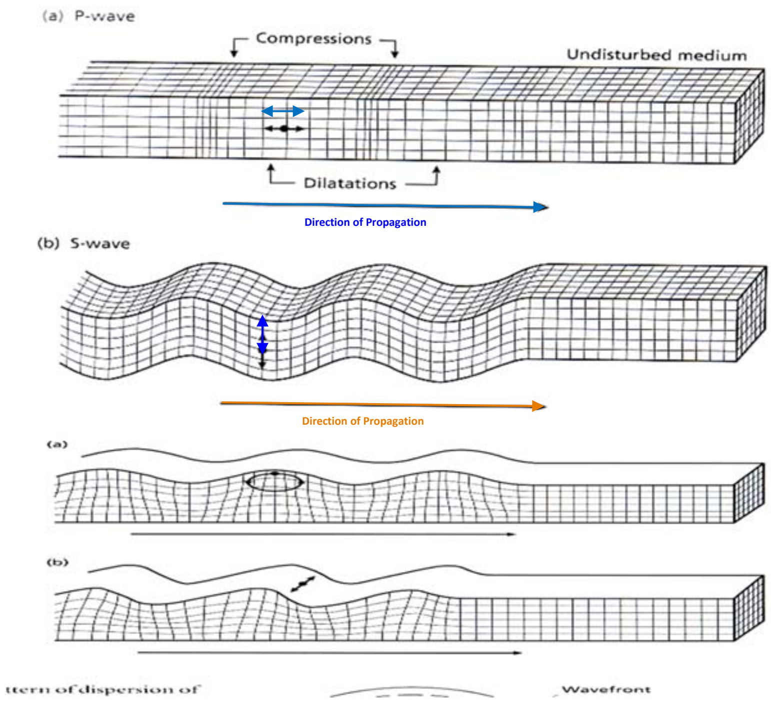
Also called: secondary wave, transverse wave, rotational wave, distortional wave, equivolumnar wave, tangential wave

Surface waves

Also called: interface wave, long wave

- **"Rayleigh waves"**
- **"Love waves"**

Seismic waves propagation



P waves

S waves

Rayleigh waves

Love waves

Each medium has the following mechanical parameters:

- Propagation velocity for Compressional waves : V_p
- Propagation velocity for Shear waves : V_s
- Density : ρ

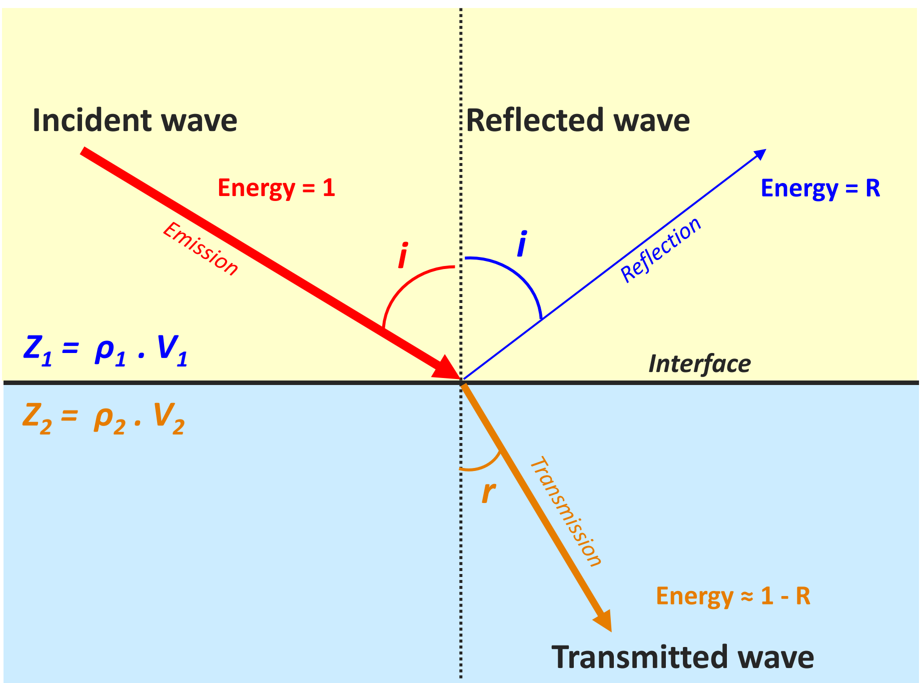
Rock velocity and density

Formations	P Velocities Vp (m/s)	S Velocities Vs (m/s)	Densities P (g/cm³)
Rubbish, Soil	300 – 700	100 – 300	1,7 – 2,4
Dry Sand	400 – 1200	100 – 500	1,5 – 1,7
Wet Sand	1500 – 4000	400 – 1200	1,9 – 2,1
Shale, Clay	1100 – 2500	200 – 800	2,0 – 2,4
Marl	2000 – 3000	750 – 1500	2,1 – 2,6
Sandstone	3000 – 4500	1200 – 2800	2,1 – 2,4
Limestone	3500 – 6000	2000 – 3300	2,4 – 2,7
Chalk	2300 – 2600	1100 – 1300	1,8 – 2,3
Salt, Anhydrite	4000 – 5500	2200 – 3100	2,1 – 3,0
Dolomite	3500 – 6500	1900 – 3600	2,5 – 2,9
Granite	4500 – 6000	2500 – 3300	2,5 – 2,7
Basalt	5000 – 6000	2800 – 3400	2,7 – 3,1
Coal	2200 – 2700	1000 – 1400	1,3 – 1,8
Water	1450 – 1500	-	1,0
Oil	1200 – 1250	-	0,6 – 0,9

Principles of waves propagation

Plane incident wave propagating within an elastic and isotropic medium

Acoustic parameters:
Density (ρ), Velocity (V),
Acoustic impedance (Z)



V_1 = medium 1 velocity
V_2 = medium 2 velocity,
i = angle of incidence = angle of reflection within medium 1
r = angle of refraction within medium 2

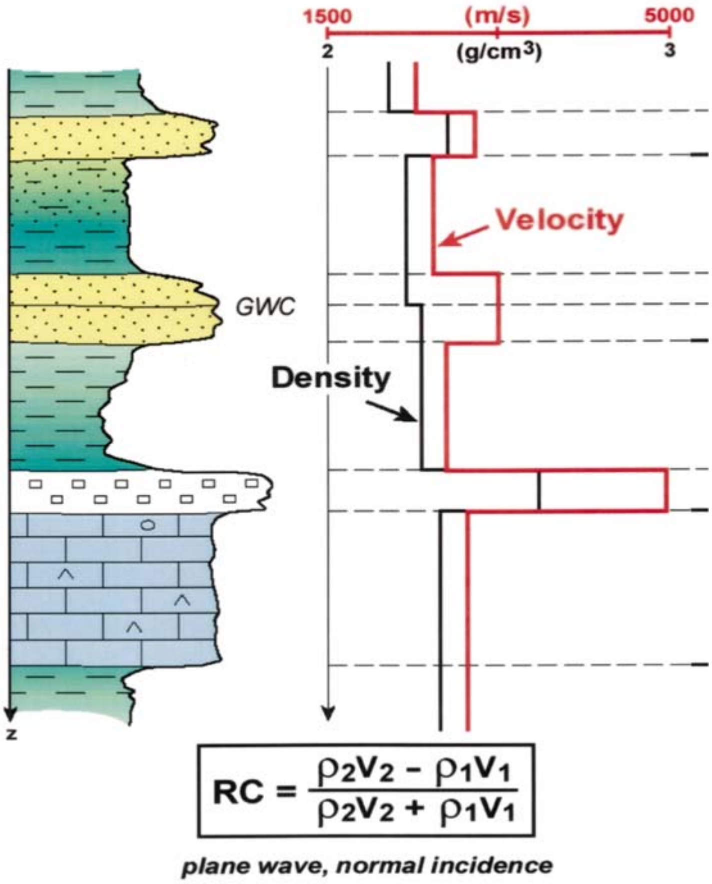
Orthogonal incidence (i ≈ 0°)

Snell-Descartes' law

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2} \quad \text{or} \quad \frac{\sin i}{V_1} = \frac{\sin r}{V_2} = \frac{\sin i_i}{V_i}$$

From geological layers to reflection coefficients

- V = 2 500 m/s – ρ = 2,2 g/cm^3
- V = 3 200 m/s – ρ = 2,4 g/cm^3
- V = 2 600 m/s – ρ = 2,25 g/cm^3
- V = 3 300 m/s – ρ = 2,25 g/cm^3
- V = 3 300 m/s – ρ = 2,3 g/cm^3
- V = 2 700 m/s – ρ = 2,3 g/cm^3
- V = 5 000 m/s – ρ = 2,7 g/cm^3
- V = 2 900 m/s – ρ = 2,4 g/cm^3
- V = 2 700 m/s – ρ = 2,3 g/cm^3



Wave propagation - Key points

- **Reflection**, **Transmission, Refraction exist because of** **Velocity contrasts**
- **Amplitude contrasts exist because of** **Velocity and Density contrasts** (i.e. contrasts of acoustic impedance [AI, Z])
- **Reflection coefficient for i < 15° :** $R_{1-2} = \dfrac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$

Exploration tools & techniques

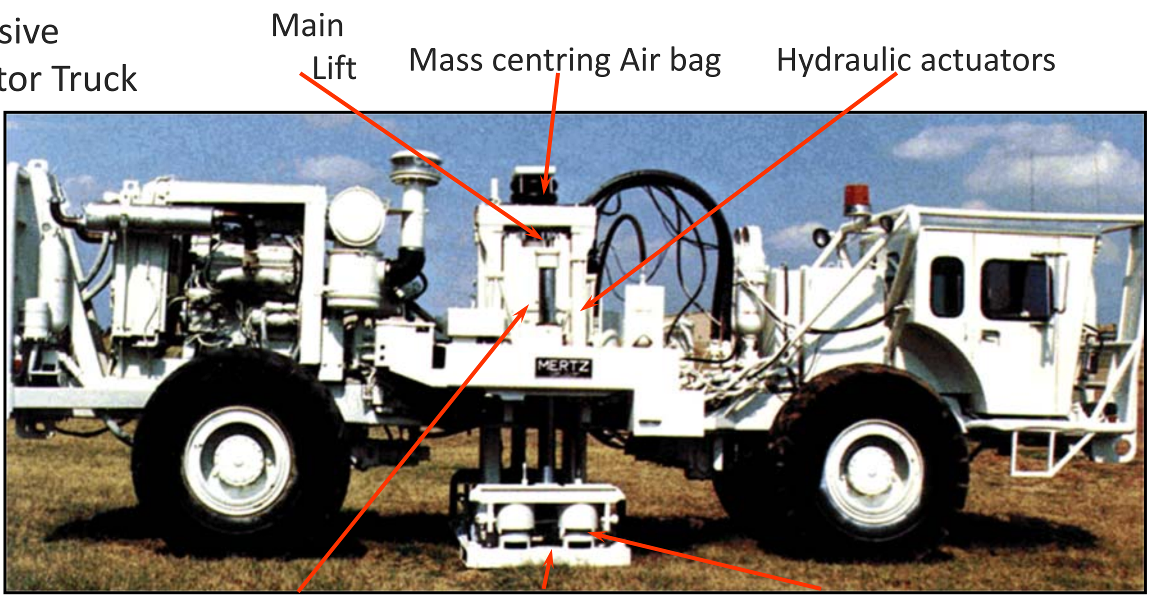
- **Petroleum geophysics**
  - Introduction to petroleum geophysics
  - Principles of seismic reflection
  - Seismic acquisition
    - Land seismic
    - Marine seismic
  - Seismic processing and imaging
  - Seismic interpretation
  - Seismic attributes and facies
  - 4D seismic

Acquisition and processing: objectives

- **The objective of seismic acquisition is to record as much as possible primary reflections (i.e. signal) and as less as possible others events (i.e. noise)**
- **The goal of seismic processing is to sort out the different types of acoustic waves in order to extract as much as possible primary reflections (as PP-waves).**

Vibrator truck: mechanical description (land seismic)

- Land seismic sources
  - Explosive
  - Vibrator Truck

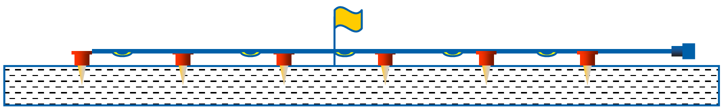


Seismic sources - Key points

- A seismic source is a device that releases energy which generates **acoustic waves** in the ground
- The main qualities for a seismic source are:
  - **Penetration capability** = Energy
  - **Resolution capability** = Wide frequency range (band)
  - **Repeatability and accuracy** = Strong quality control

Seismic receivers - Geophone

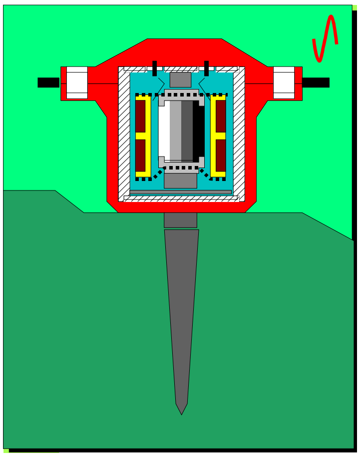
- **One-component geophone principle**
  - A ring magnet with two polar parts.
  - A coil which surrounds the magnet.
  - Springs to keep coil suspended.
  - Sealed metal case fitted with electrodes.
  - A plastic protective case with a metal spike.
  - The spike ensure the best ground coupling.



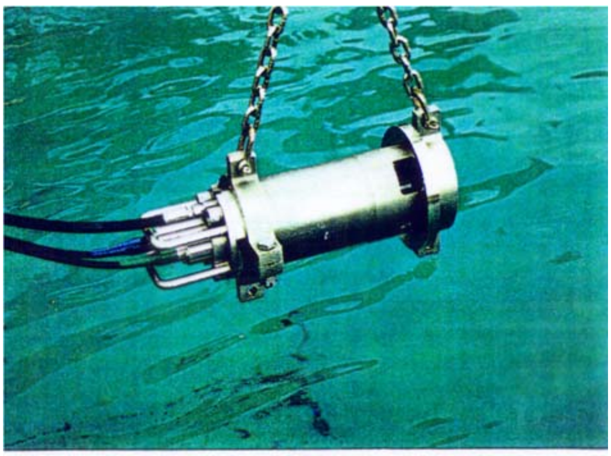
String of 6 geophones

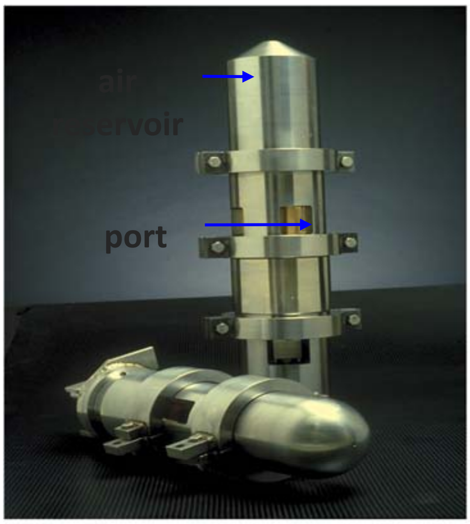
Detector sensitive to particle motion
Transforms seismic energy into electrical voltage

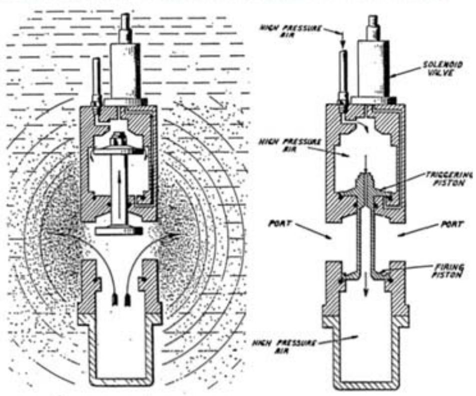
- **Vertical**
- **Horizontal**
- **3-Components**



Marine seismic source: Airguns (offshore seismic)



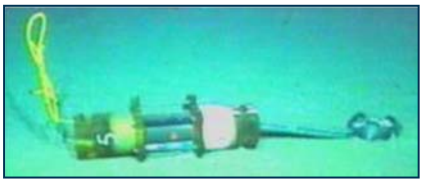


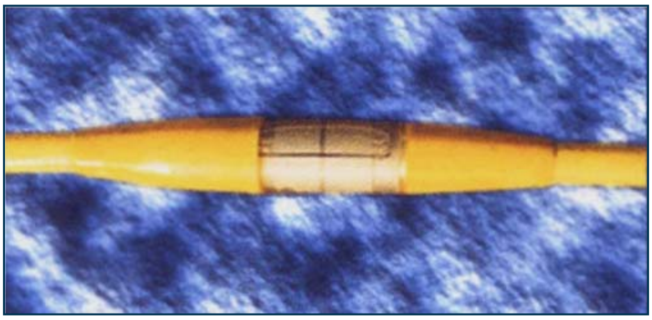


Seismic receivers - Hydrophone

Detector sensitive to pressure variations
Transforms seismic energy into electrical voltage

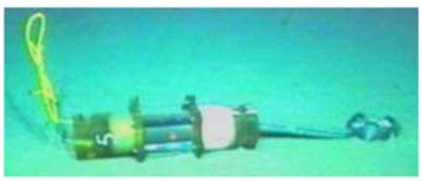
Hydrophones and streamer



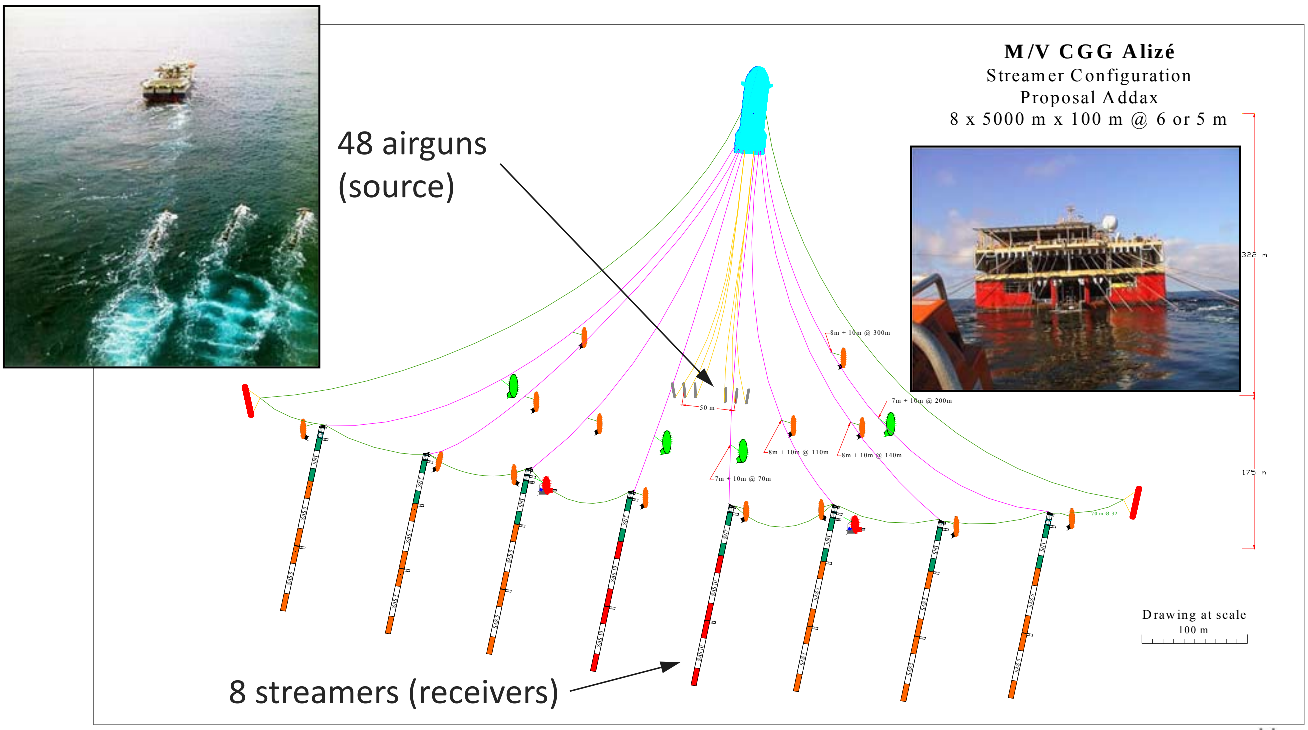


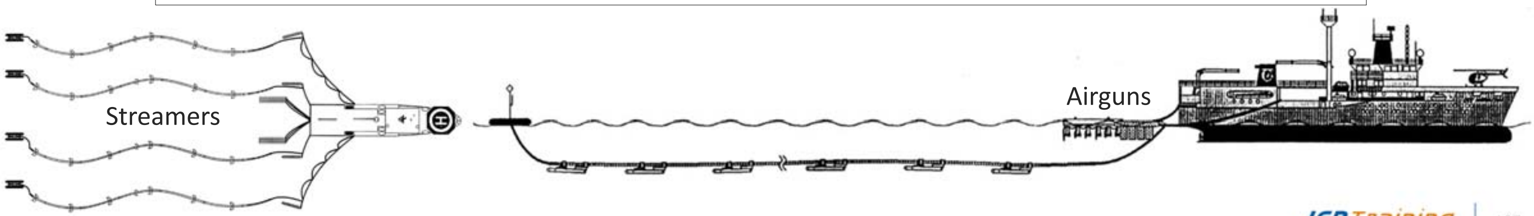
Seismic receivers

- **Geophone:**
  - Detector sensitive to particle motion
  - Transforms seismic energy into electrical voltage
    - Vertical
    - Horizontal
    - 3 Components
- **Hydrophone:**
  - Detector sensitive to pressure variations
  - Transforms seismic energy into electrical voltage
- **…**

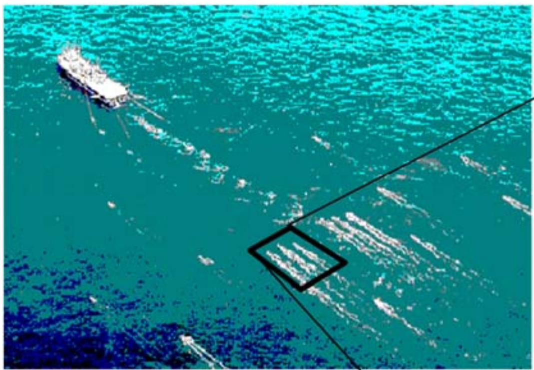


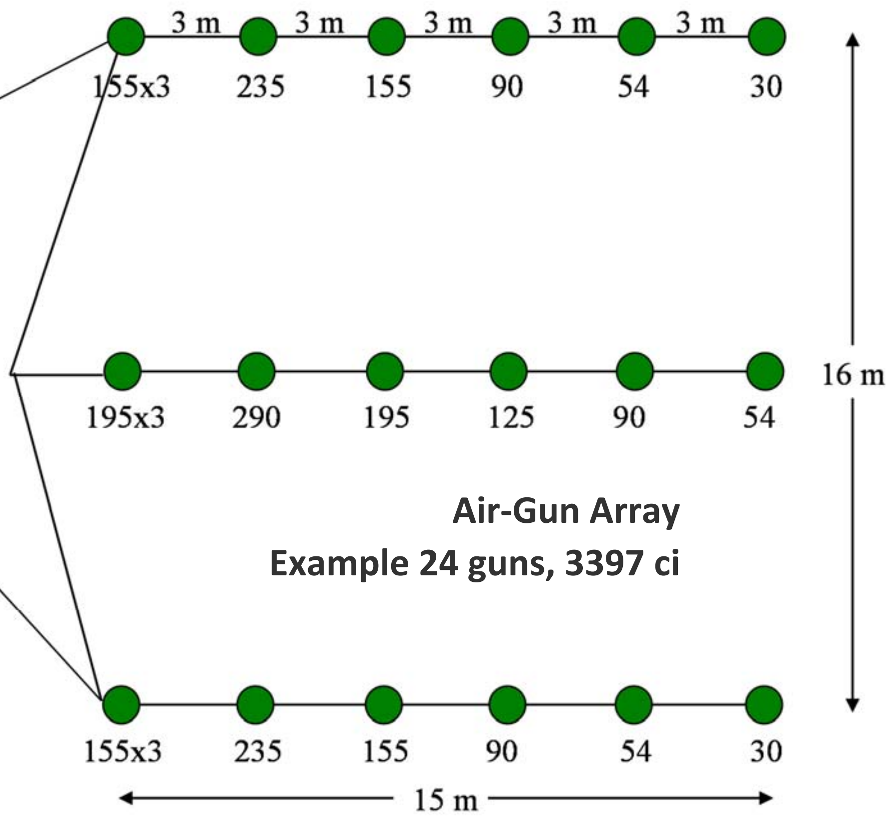
Marine seismic acquisition set-up



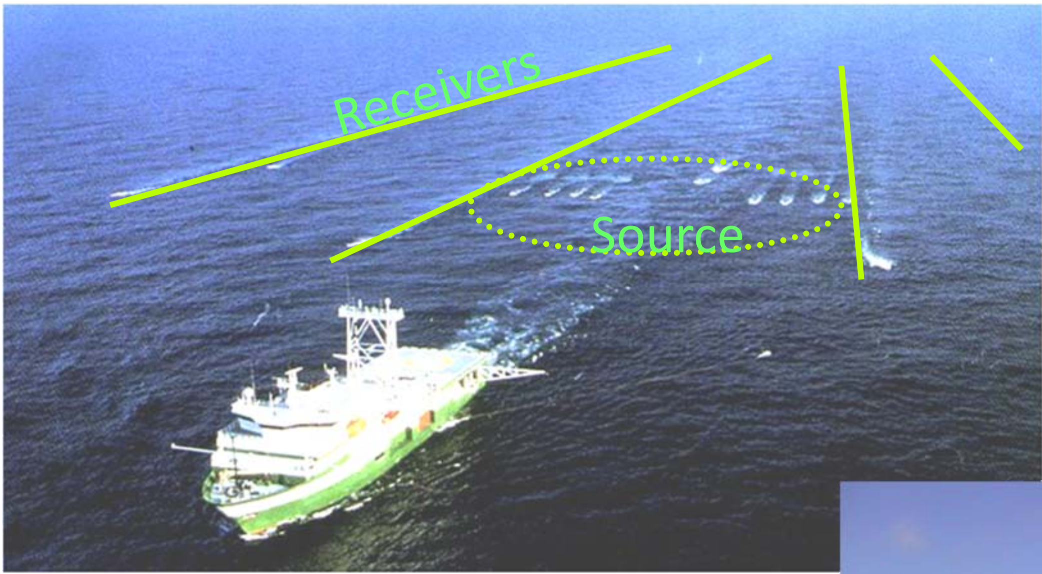


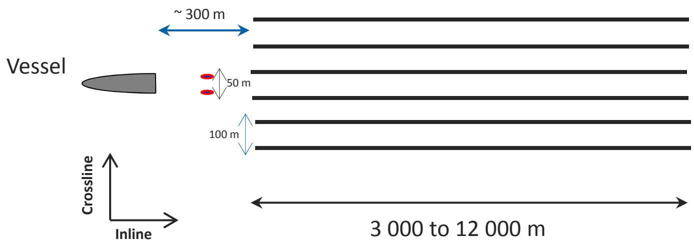
Airgun array horizontal geometry



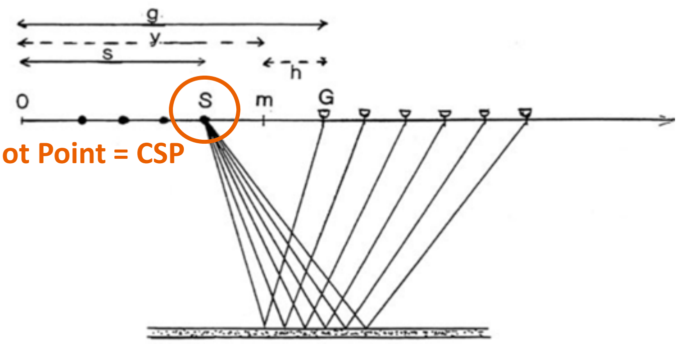


Specific vessels for seismic …





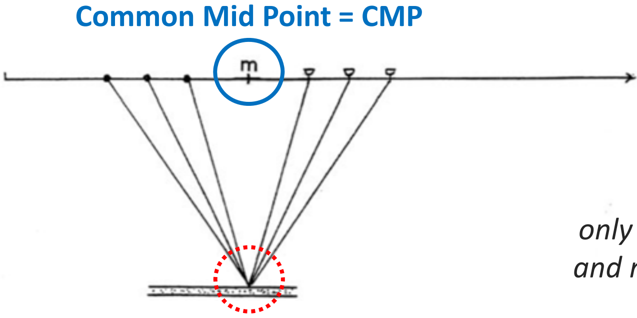
Acquisition set up and geometry - Shot gather



Off-end geometry

Marine acquisition

Common Mid Point = CMP



Common Depth Point = CDP

Split-spread geometry

Land acquisition

CMP = CDP
only when reflector is horizontal
and medium horizontally layered

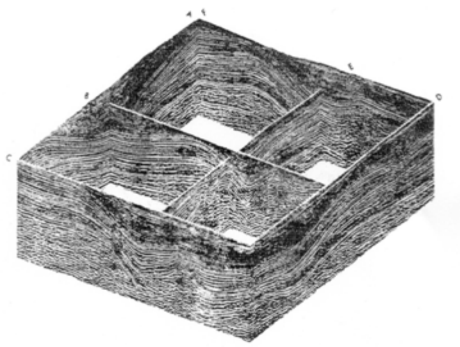
Exploration tools & techniques

- **Petroleum geophysics**
  - Introduction to petroleum geophysics
  - Principles of seismic reflection
  - Seismic acquisition
    - Land seismic
    - Marine seismic
  - Seismic processing and imaging
  - Seismic interpretation
  - Seismic attributes and facies
  - 4D seismic

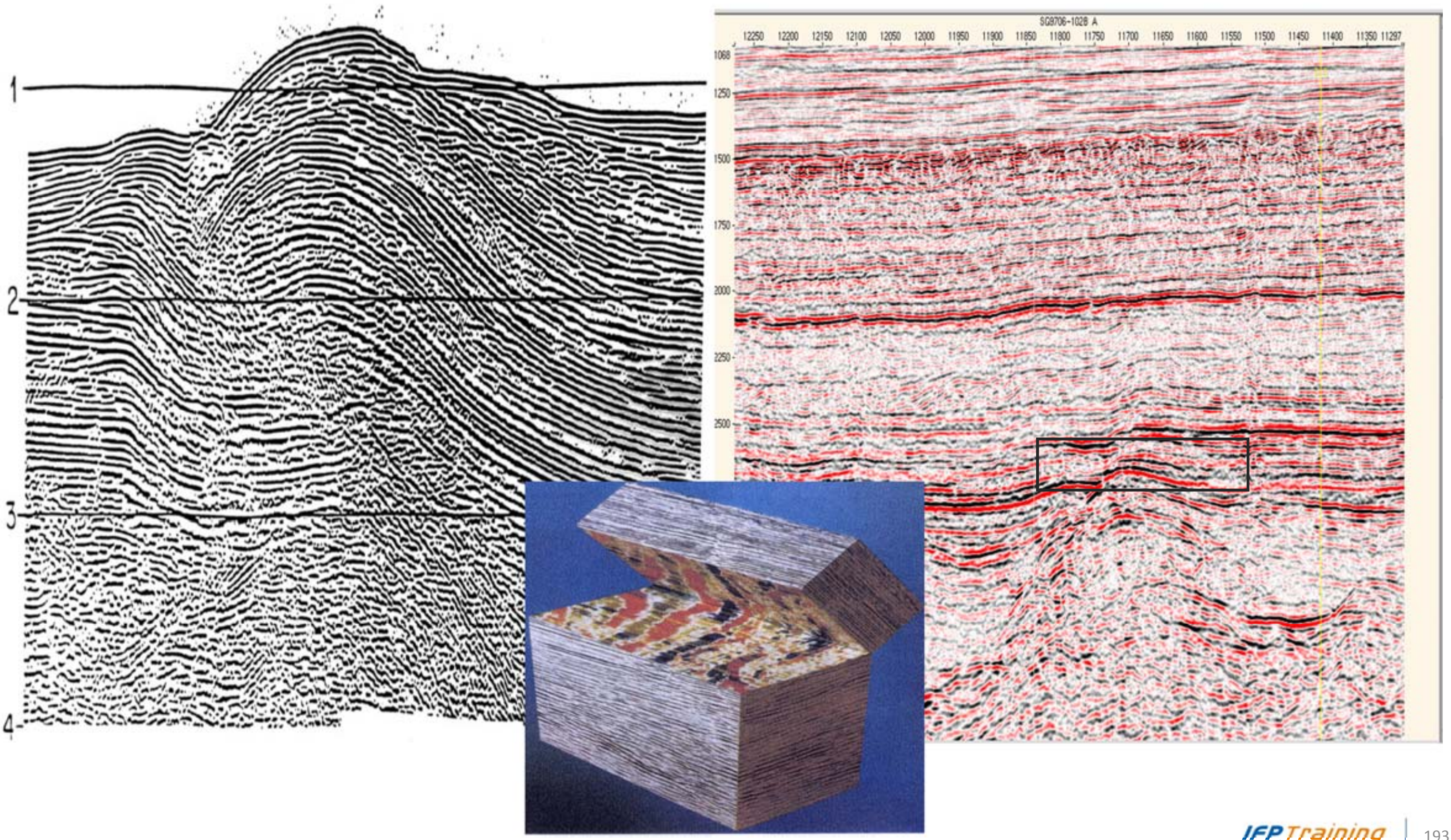
Seismic processing

- **The main objective of seismic processing is to separate different wave trains, and extract as much as possible primary reflections.**
- **By changing the field raw seismic data, usually to improve the signal-to-noise ratio, so as to facilitate geological interpretation of the subsurface.**

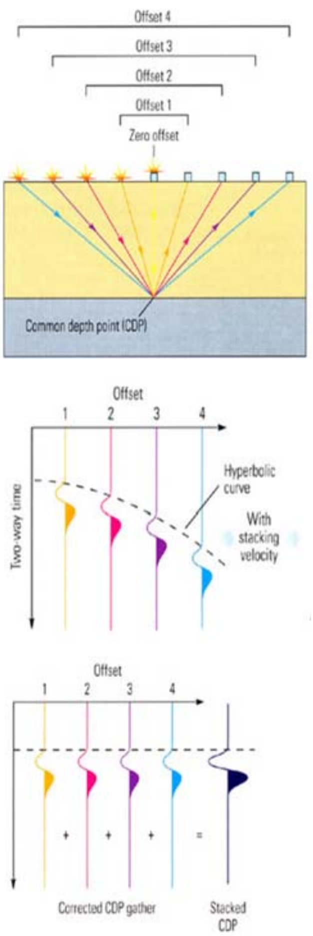
- **Seismic Processing results are:**
  - 2D seismic sections
  - 3D seismic cubes



Final documents: 2D sections or 3D Blocks

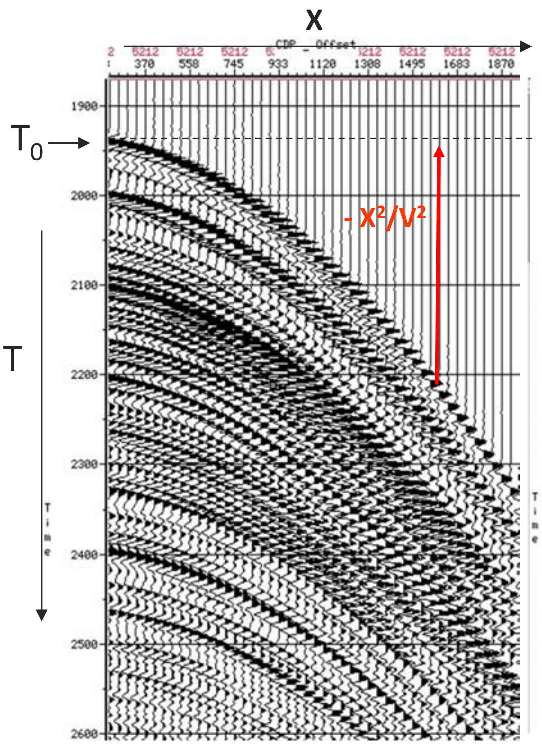


Seismic « stack » in multiple coverage

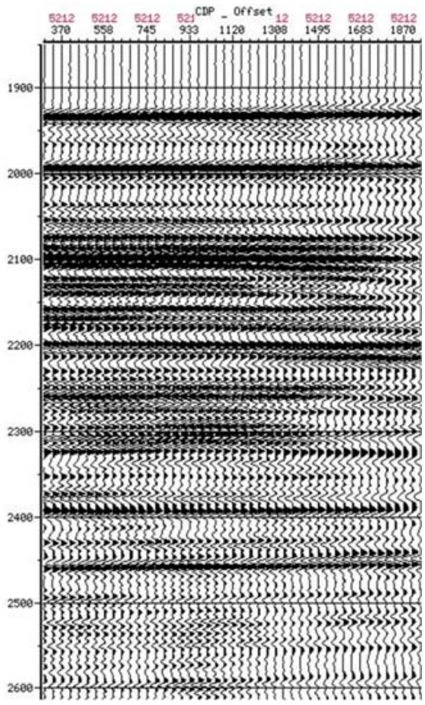


Stacking → attenuation of signal/noise ratio

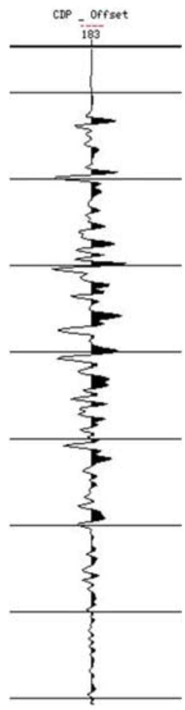
ORIGINAL CMP gather



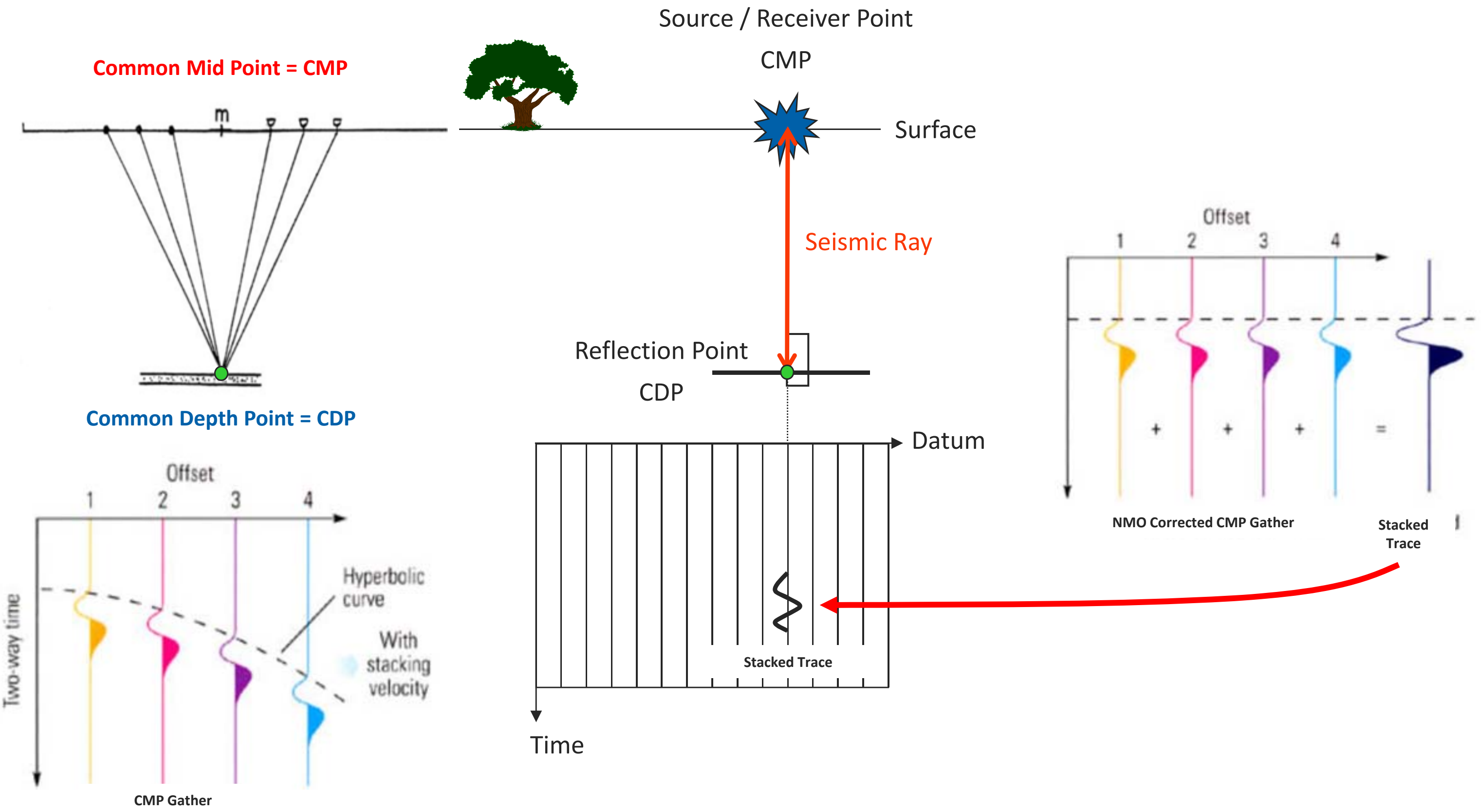
CMP gather
after velocity (NMO) correction



Stacked
CMP gather

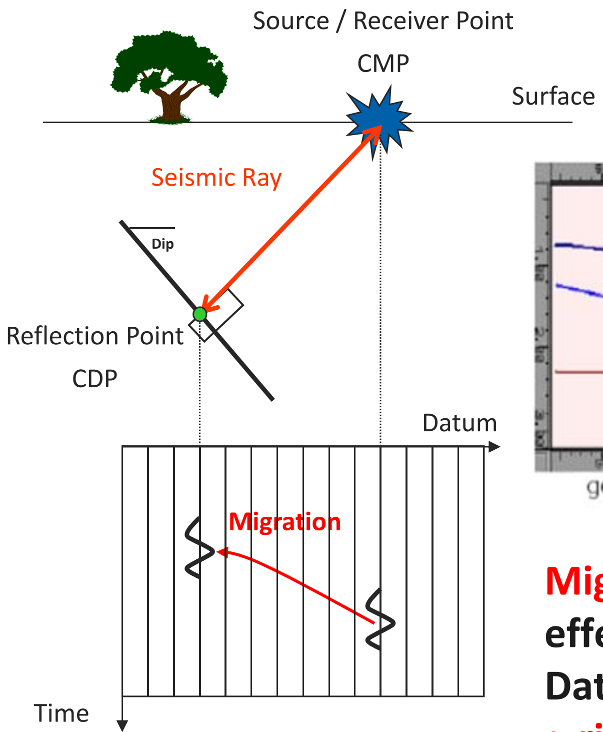


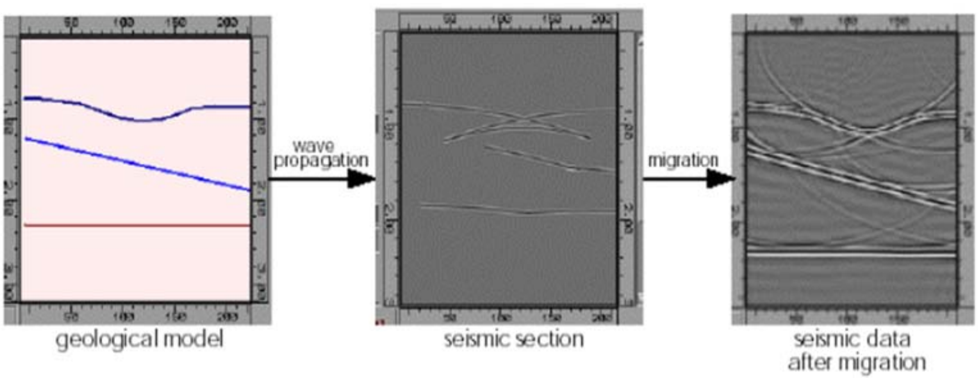
What is the stack result? Vertical stack!



If DIP, vertical stack is not at the right place!

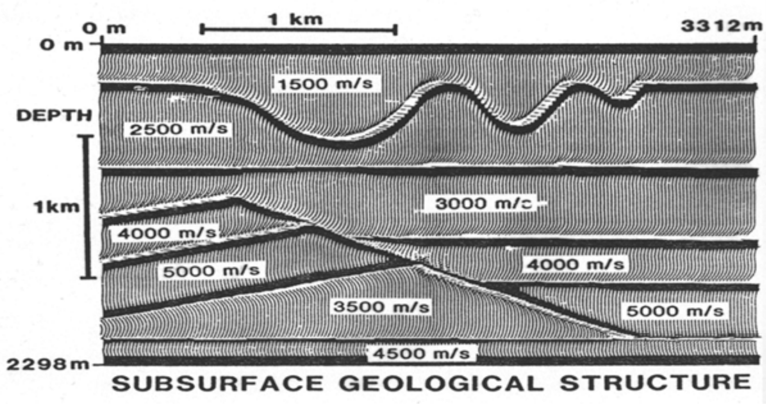
We need « seismic migration »

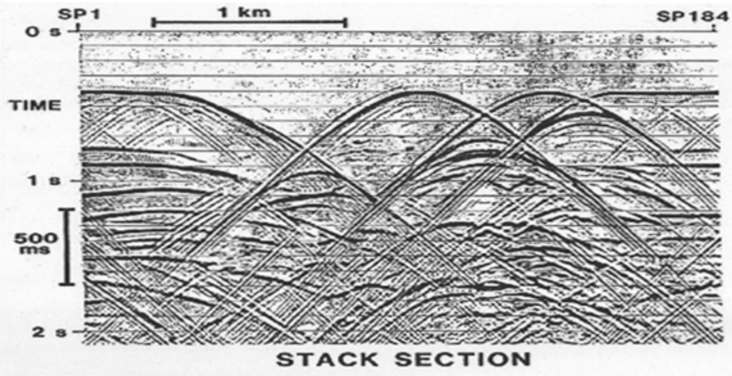




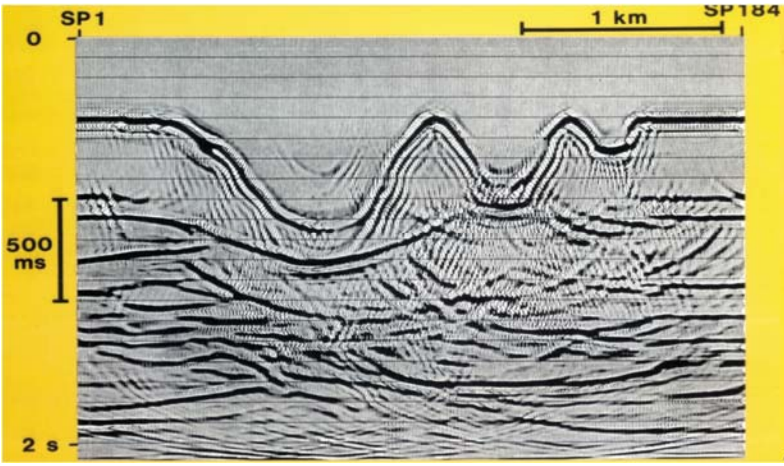
Migration is the Process which removes the effect of Wave Propagation from the Seismic Data and which put the Seismic Events at the « right place »!

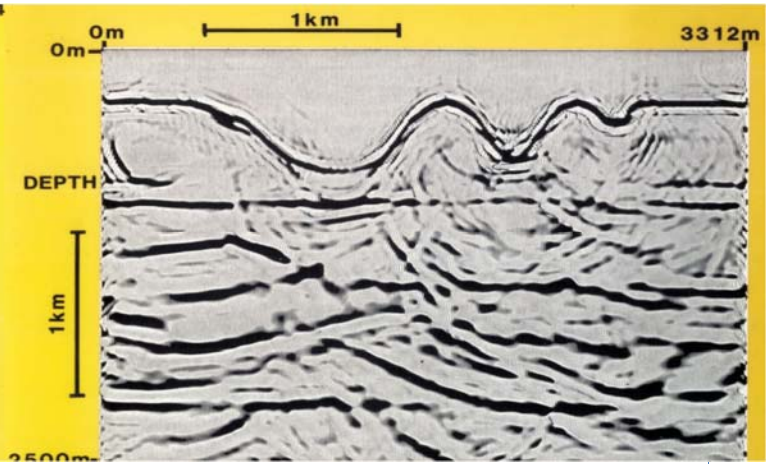
Geology versus stack section (time)





POST-STACK: TIME MIGRATION versus DEPTH MIGRATION





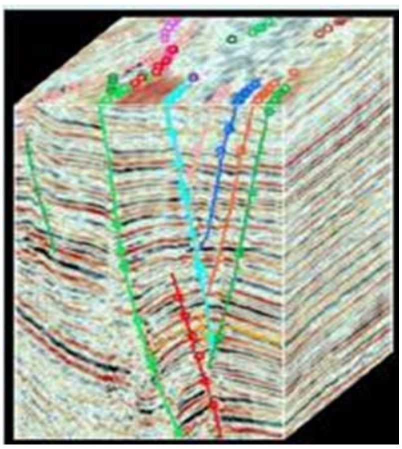
Seismic processing and imaging - Key points

- **Seismic processing is an iterative process.**
  - Several steps require iteration, such as:
    - Static corrections, Velocity analysis, Stack, Migration, …

Exploration tools & techniques

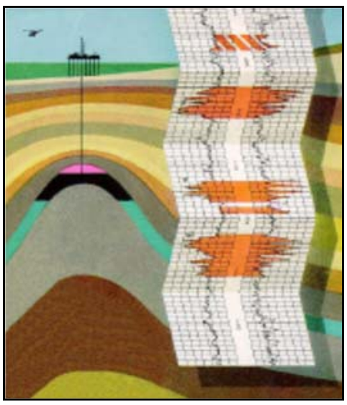
- **Petroleum geophysics**
  - Introduction to petroleum geophysics
  - Principles of seismic reflection
  - Seismic acquisition
    - Land seismic
    - Marine seismic
  - Seismic processing and imaging
  - Seismic interpretation
  - Seismic attributes and facies
  - 4D seismic

Seismic interpretation workflow

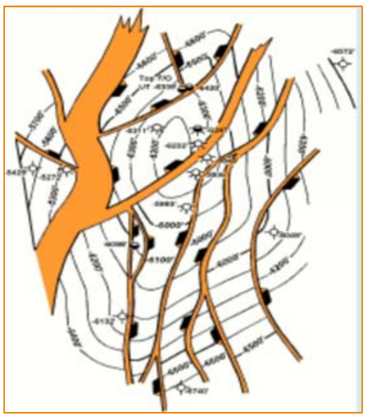


Seismic data

+



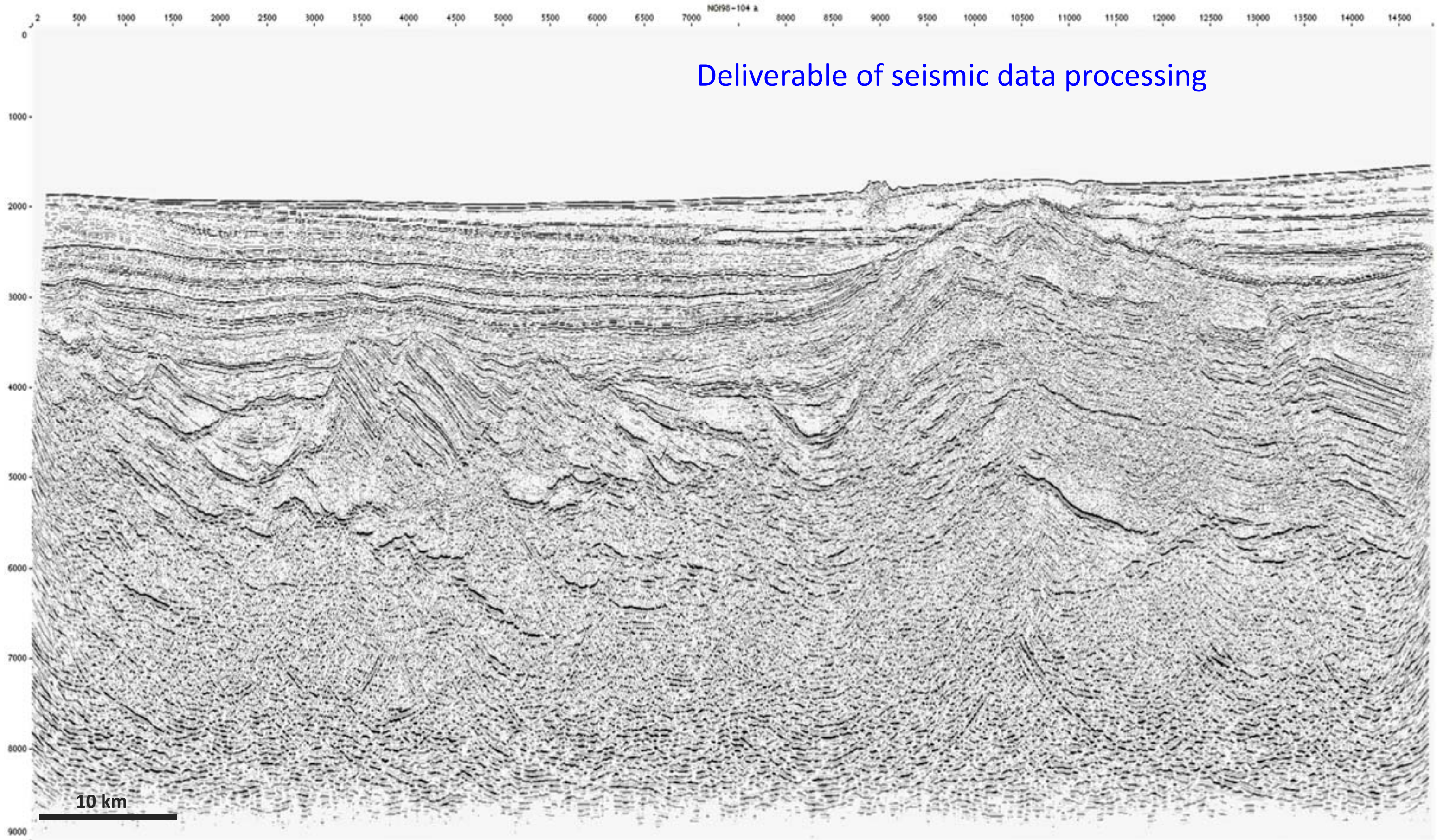
Well data



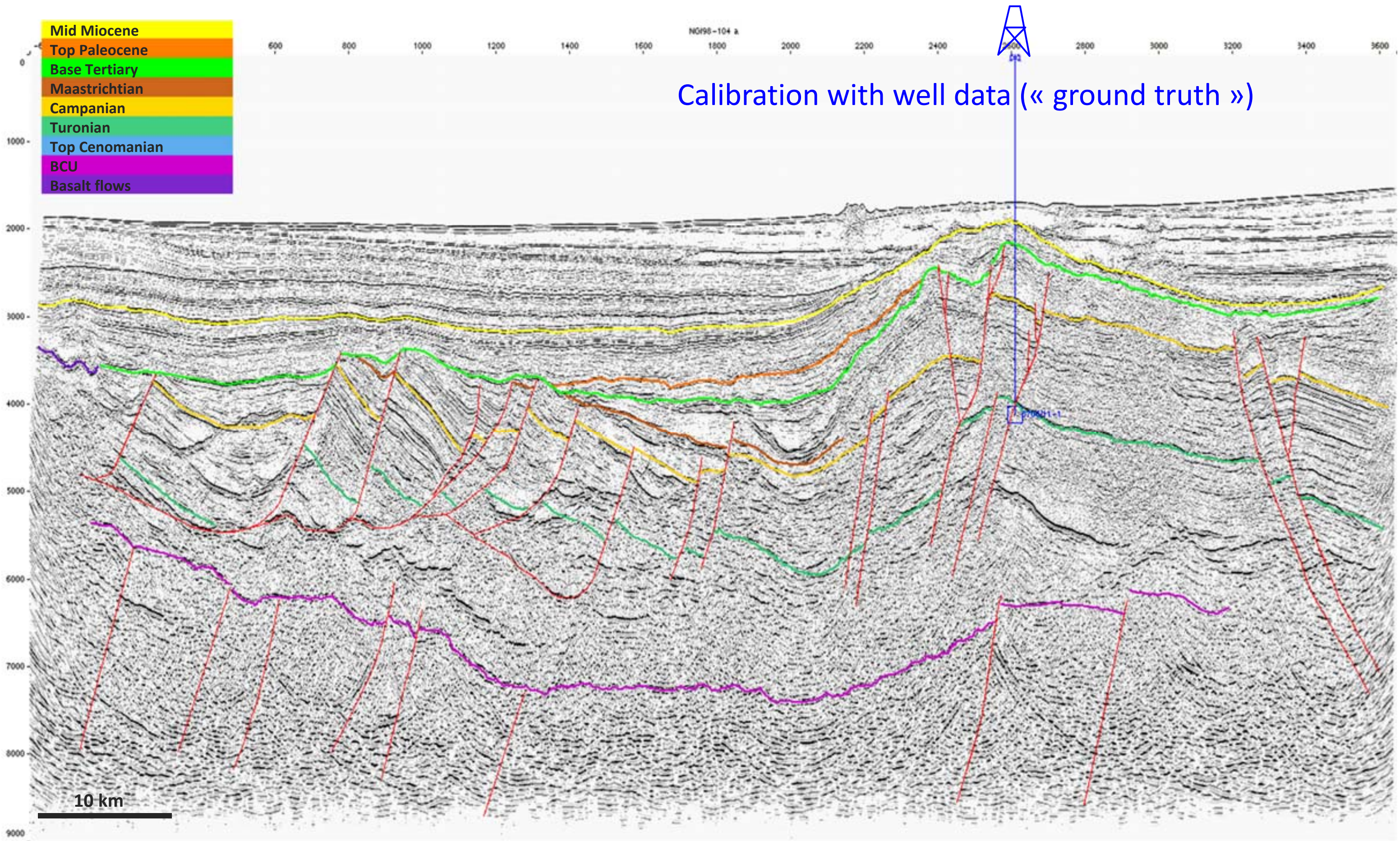
Isochron map of seismic horizon (top/base)

Fault analysis

Seismic section - Raw

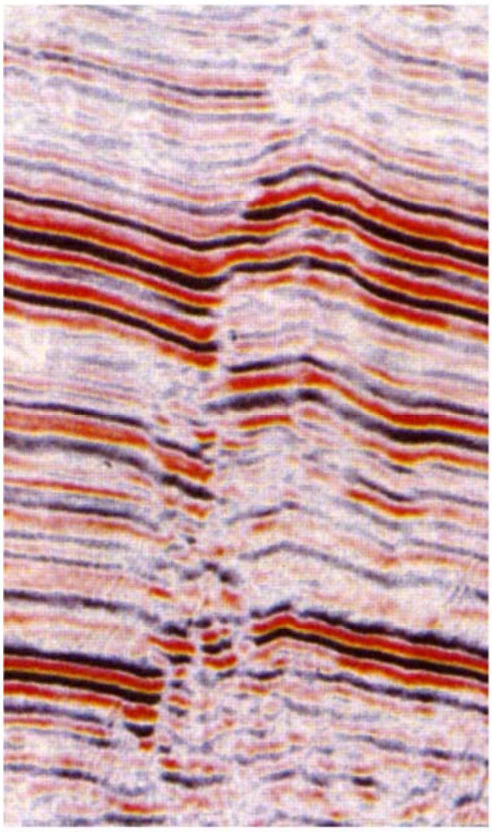


Seismic section - Interpreted

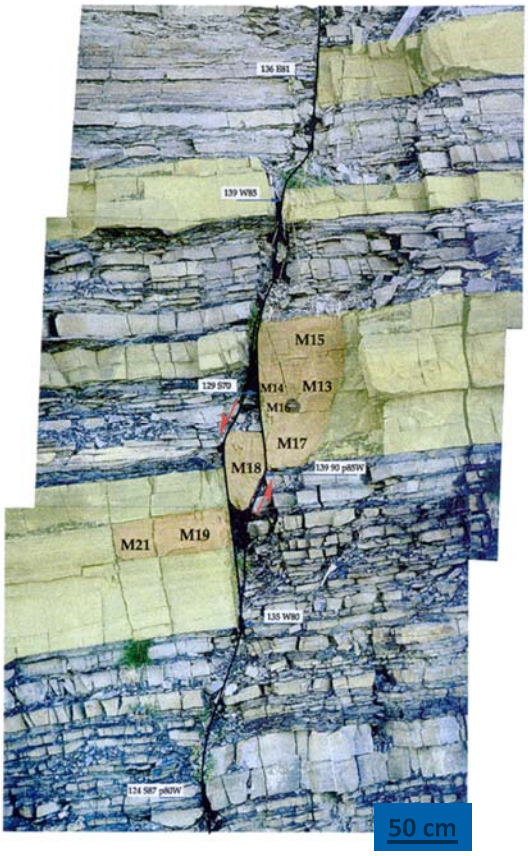


Picking faults on seismic

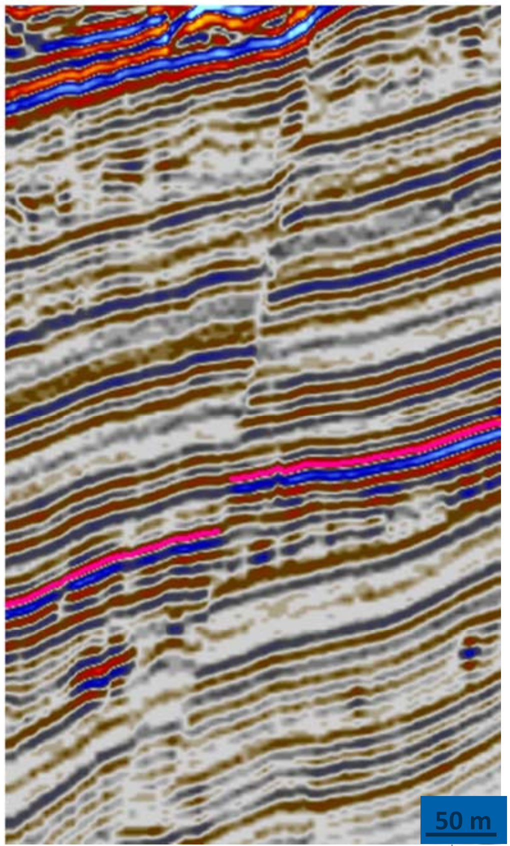
Seismic scale



Outcrop scale

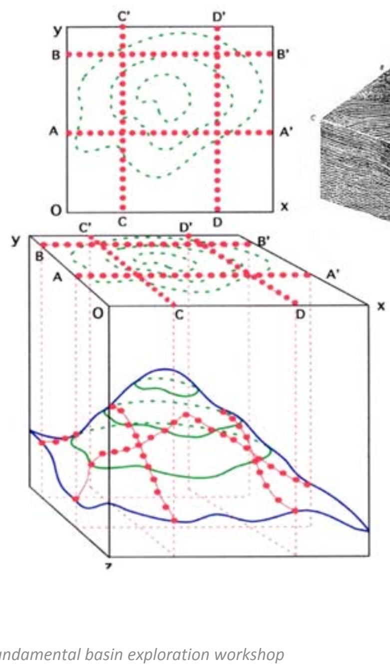


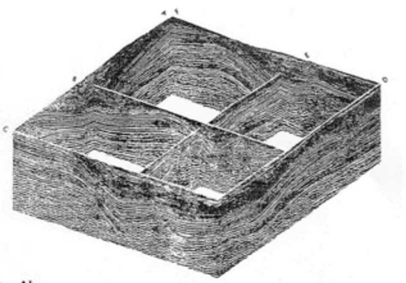
HR seismic scale



2D vs 3D seismic acquisition

- Wide, variable spacing between profiles
- Blind zones in acquisition coverage
- **Significant related uncertainty**

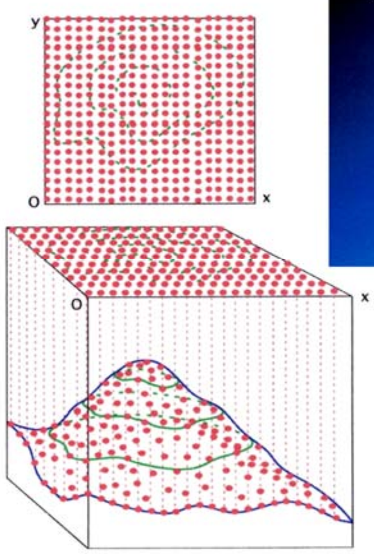


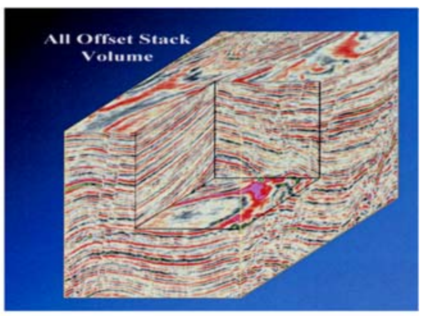


2D seismic mesh (grid)

2D seismic surface sampling
→ **Poor lateral resolution**

- Homogeneous coverage of surveyed area
- High density data sampling
  - Reduced blind zones
  - Enhanced signal quality and processing
- **Reduced related uncertainty and risks**

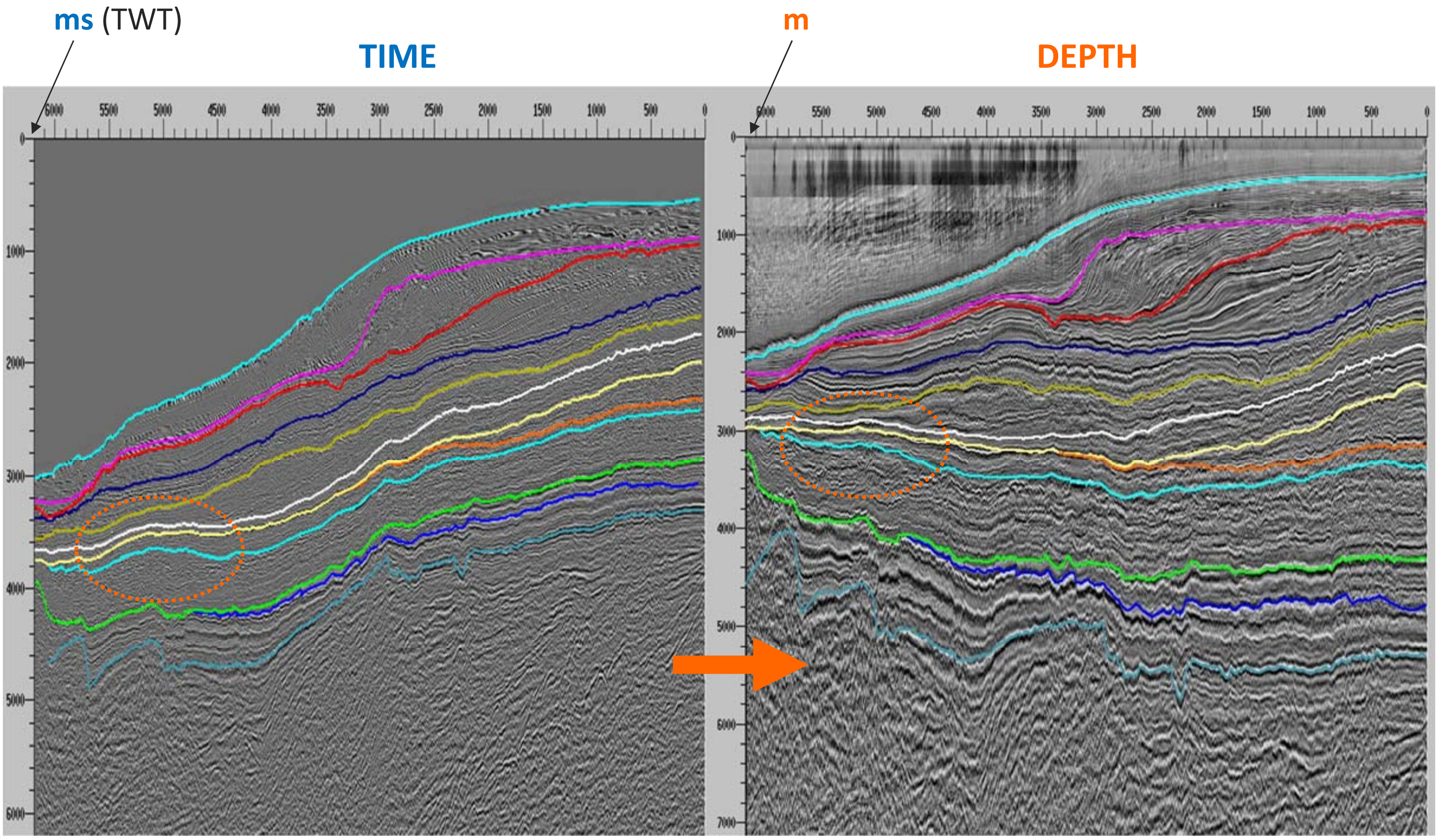




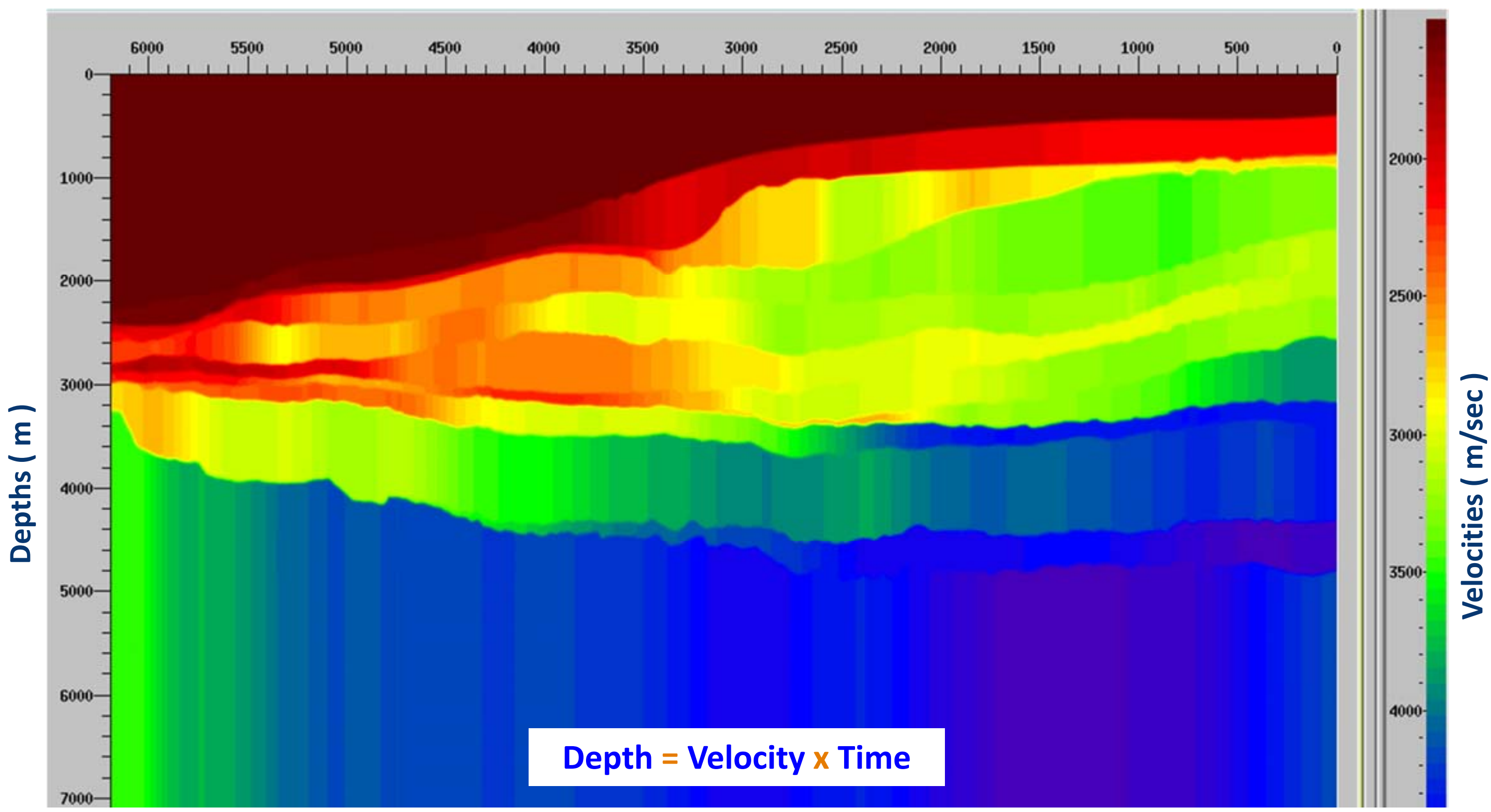
3D seismic block (cube)

3D seismic surface sampling
→ **Better lateral resolution**

Time-to-depth conversion

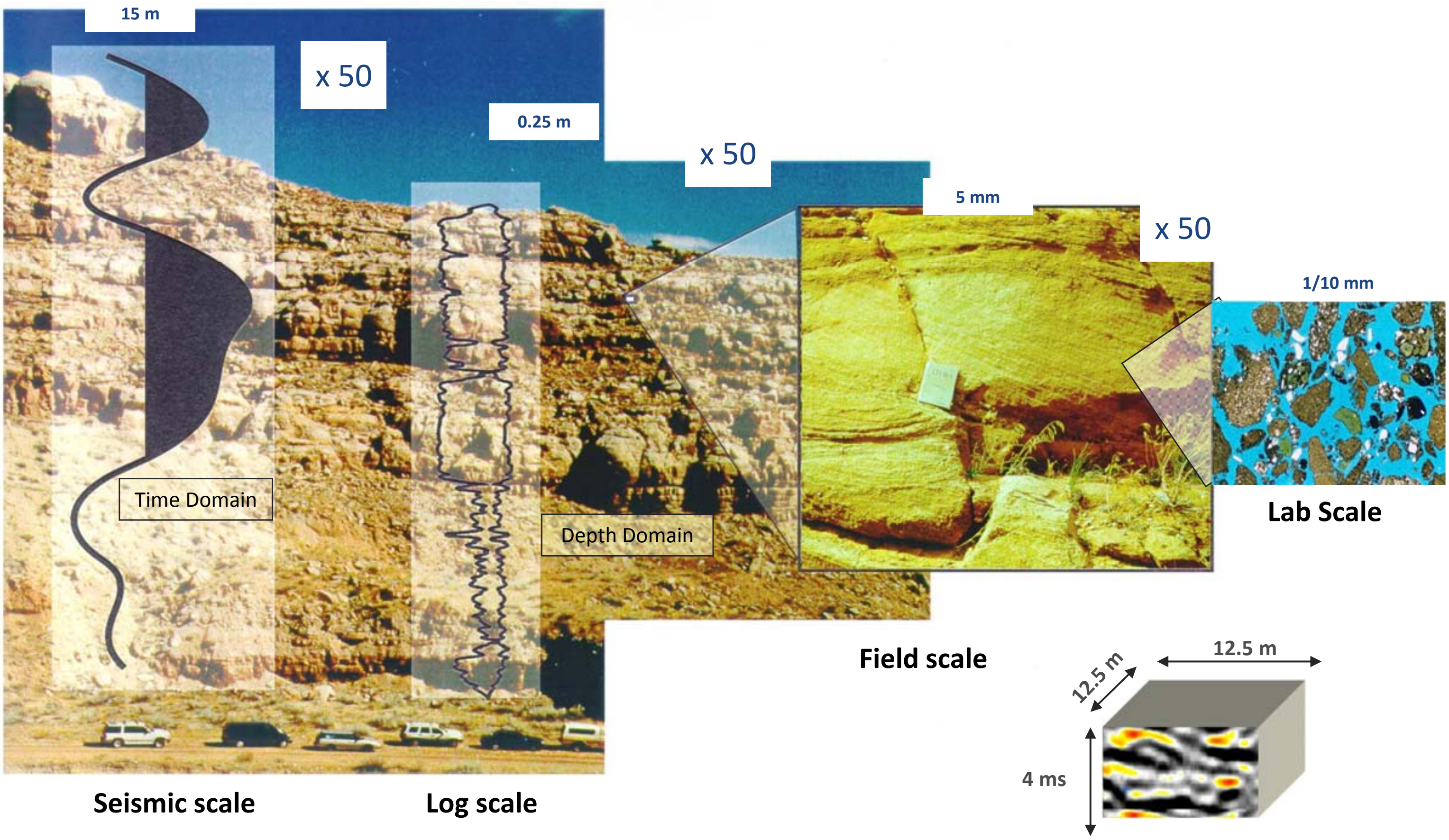


Velocity model



Quality of the **velocity model** is essential to produce reliable interpretation

Scaling issues: the big challenge!

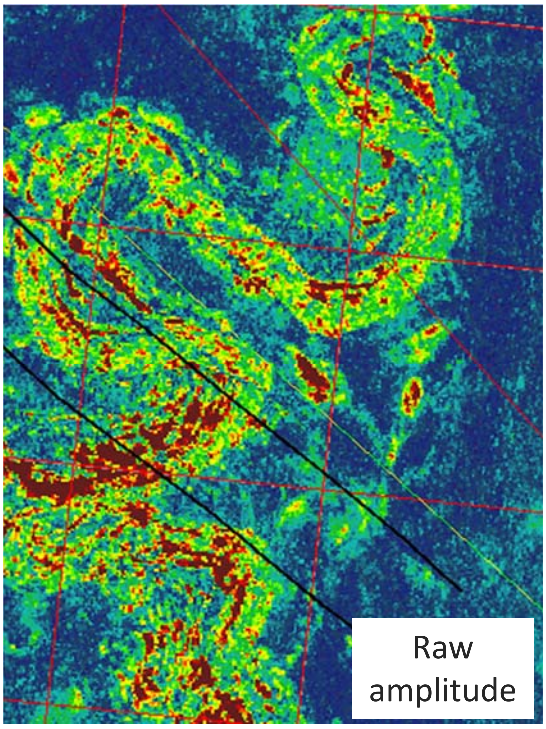


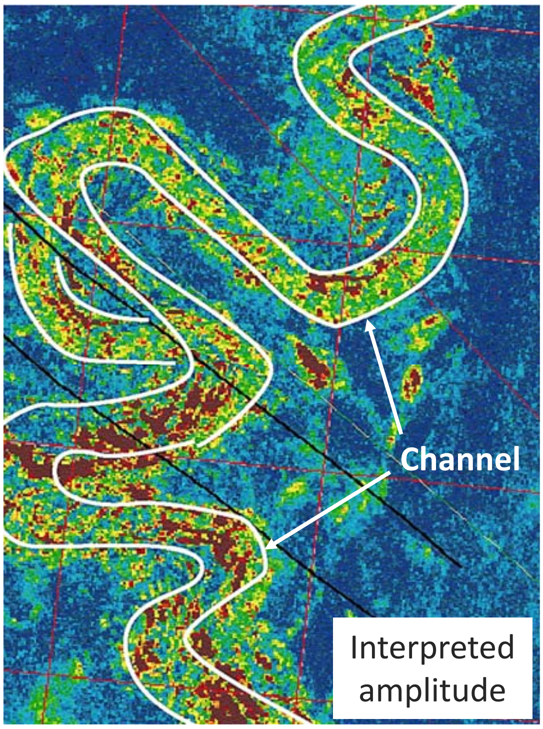
Improvement of geophysics for reservoir purpose

- **Reservoir = Rock with fluids in porosity**
  - Rock
    - 3D seismic
    - Amplitude maps & Seismic facies analysis
    - Inversion & Modeling
  - Fluids detection
    - DHI
    - Amplitude anomalies
    - 4D: fluid monitoring

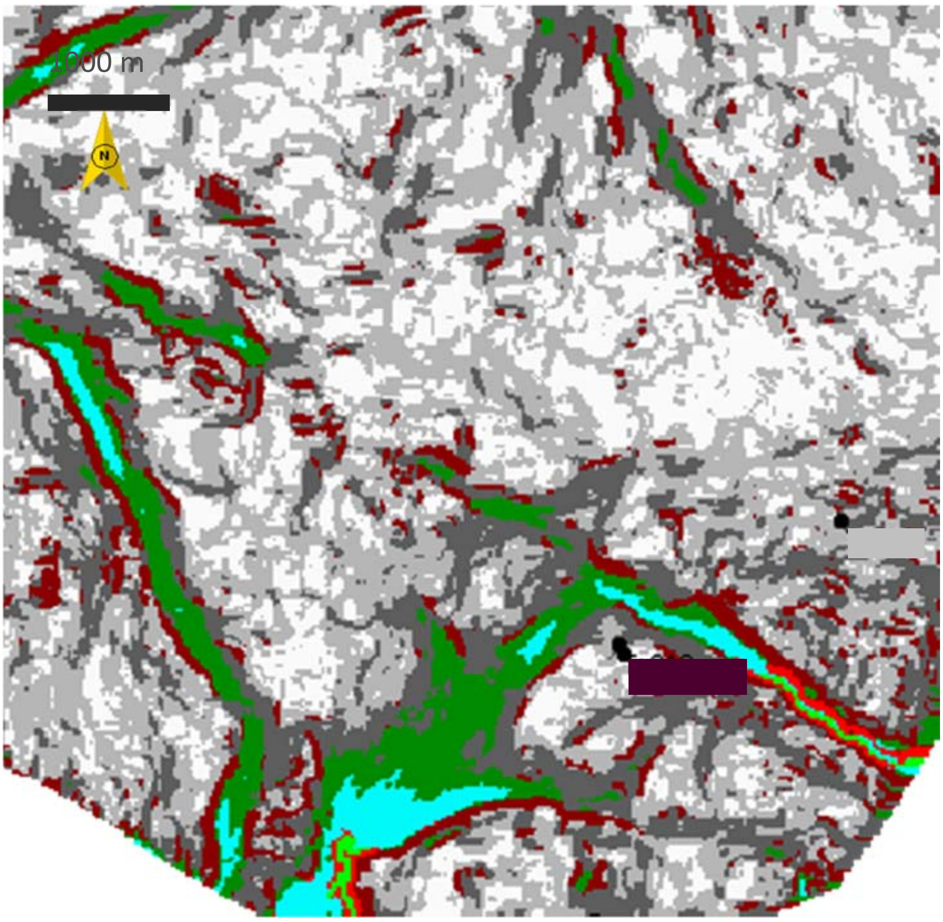
Seismic amplitudes analysis (3D time slice)

Analysis of amplitude anomalies

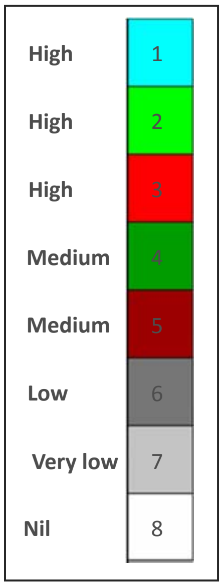




Seismic facies analysis (3D time slice)

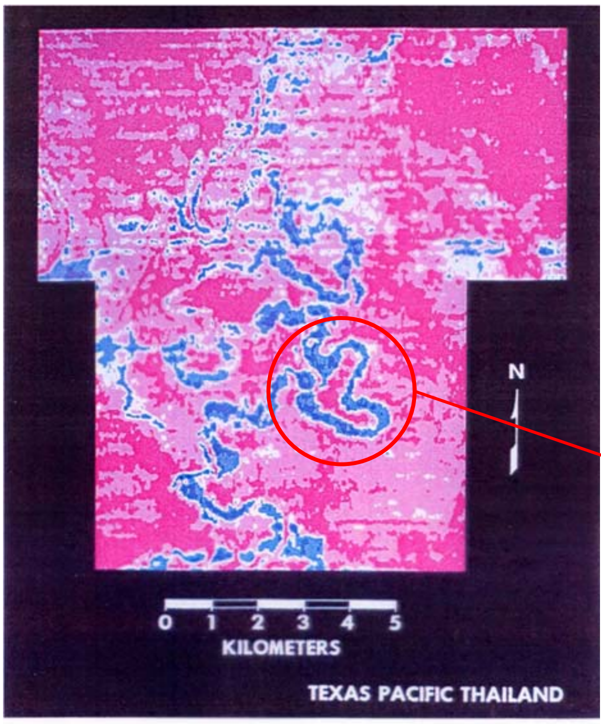


Fracture density map
based on
seismic facies
(= combination of attributes)



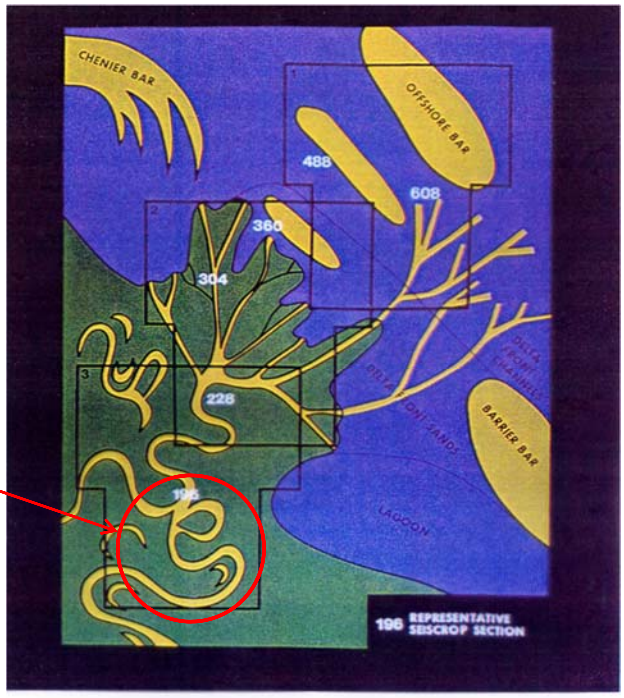
Time slice interpretation

Time slice



From AAPG mem.42

Map



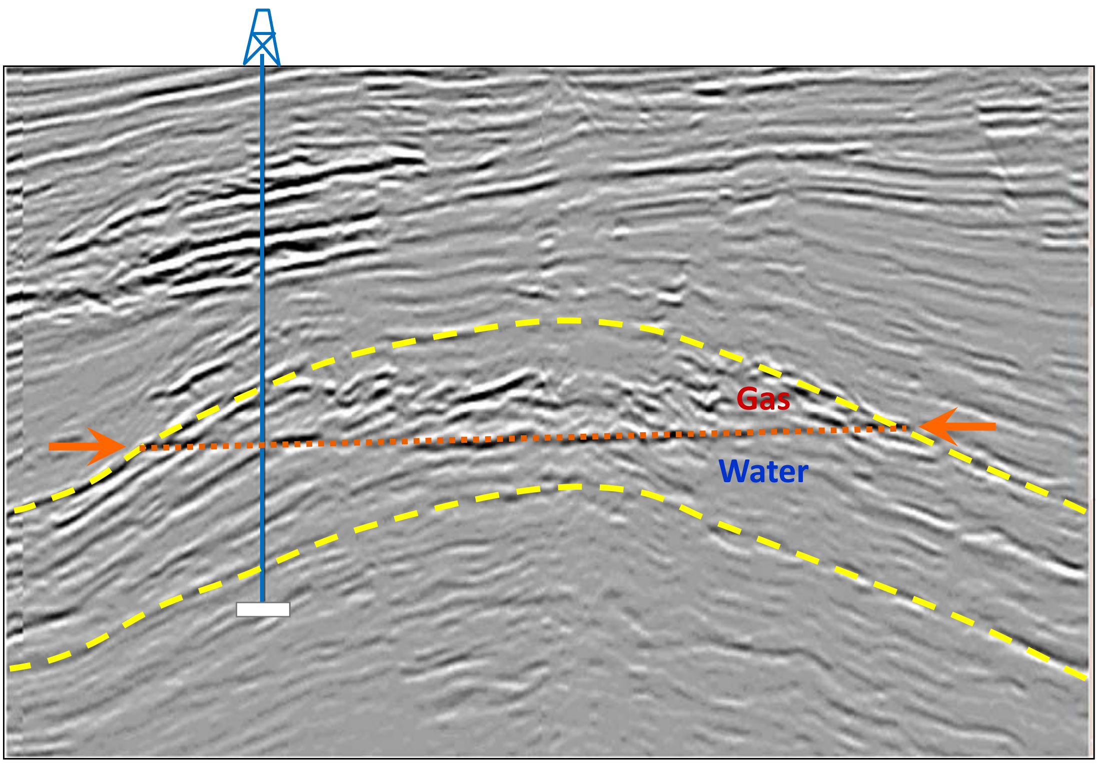
From AAPG mem.42

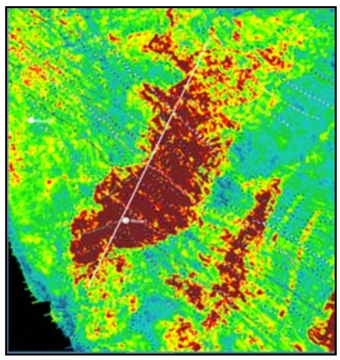
Amplitudes on time slice vs **present-day sedimentological analog** (Thailand)

Qualitative analysis of amplitudes

“Flat spot” on map & section

Well





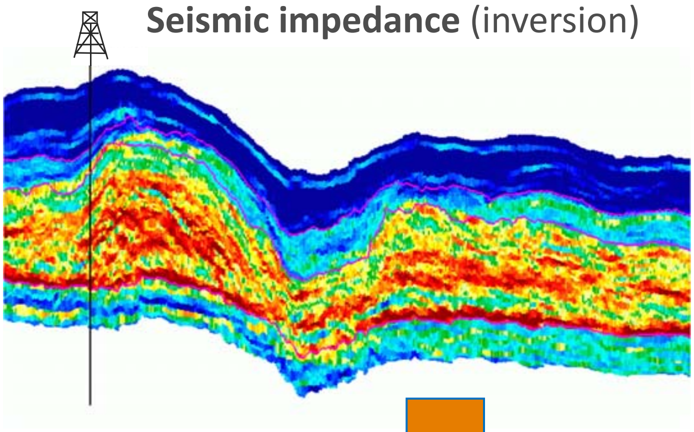
Amplitude map

W. Beydoun et al., 2000 - Courtesy TOTAL

From seismic characterization to seismic reservoir facies

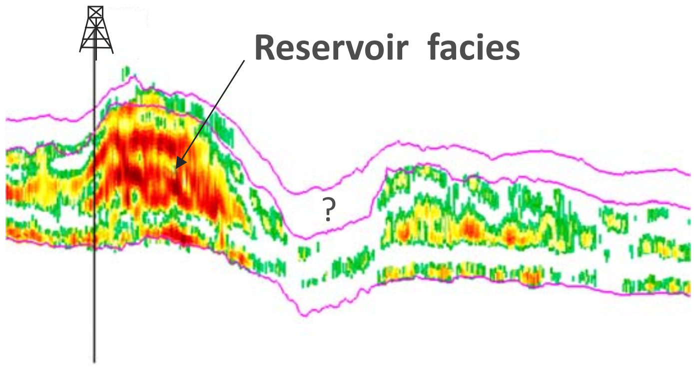
From seismic impedance to seismic facies (of the reservoir)

Seismic impedance (inversion)



Correlation of seismic facies with well data.
Only reservoir facies are plotted:
evidence of lateral discontinuity
(facies variation → reservoir quality degradation)

Reservoir facies



Well-to-seismic calibration

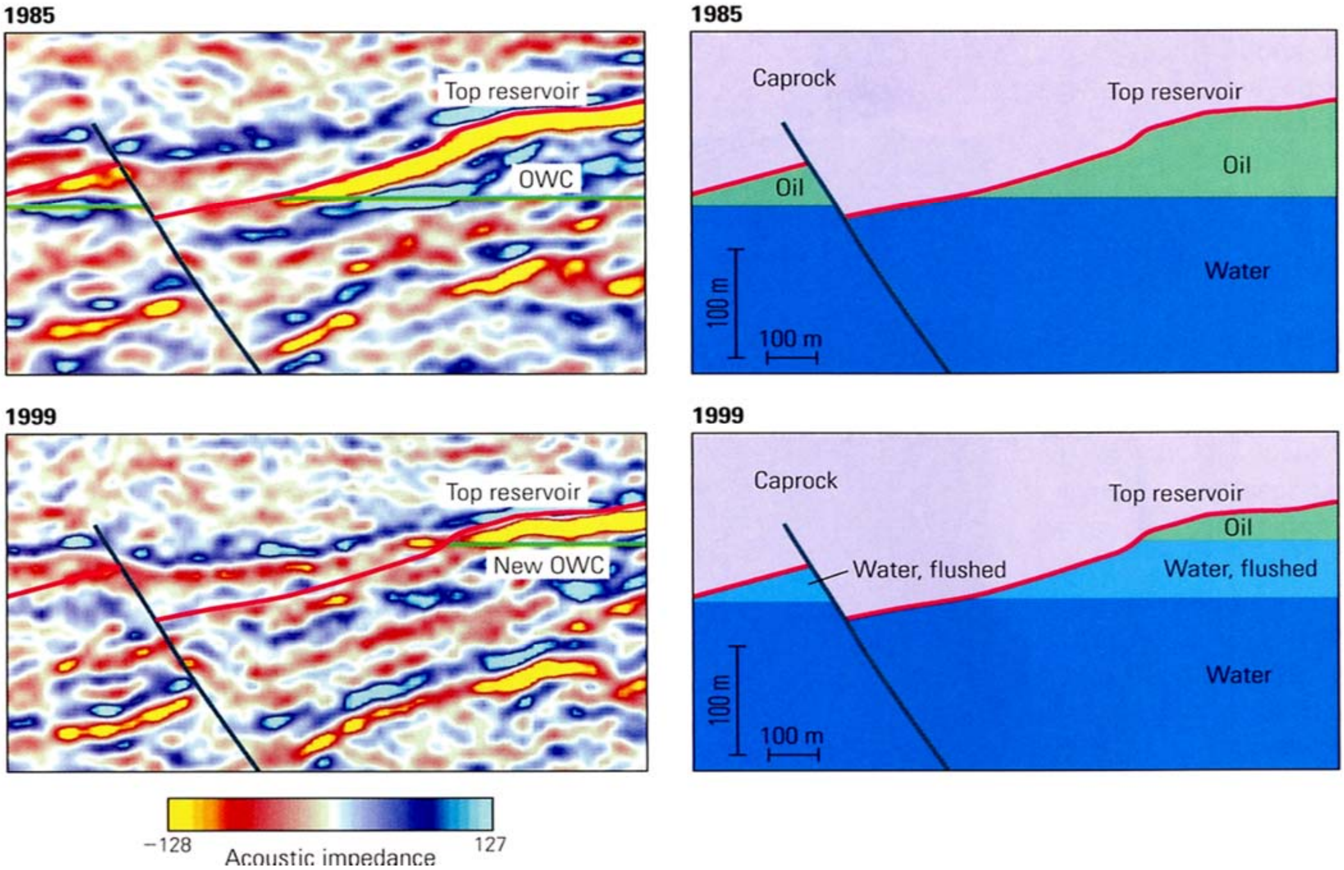
S. Gluck, E. Juve, Y. Lafet, CGG

→ **Prediction of reservoir occurrence between wells**

4D seismic - 4th dimension = Time

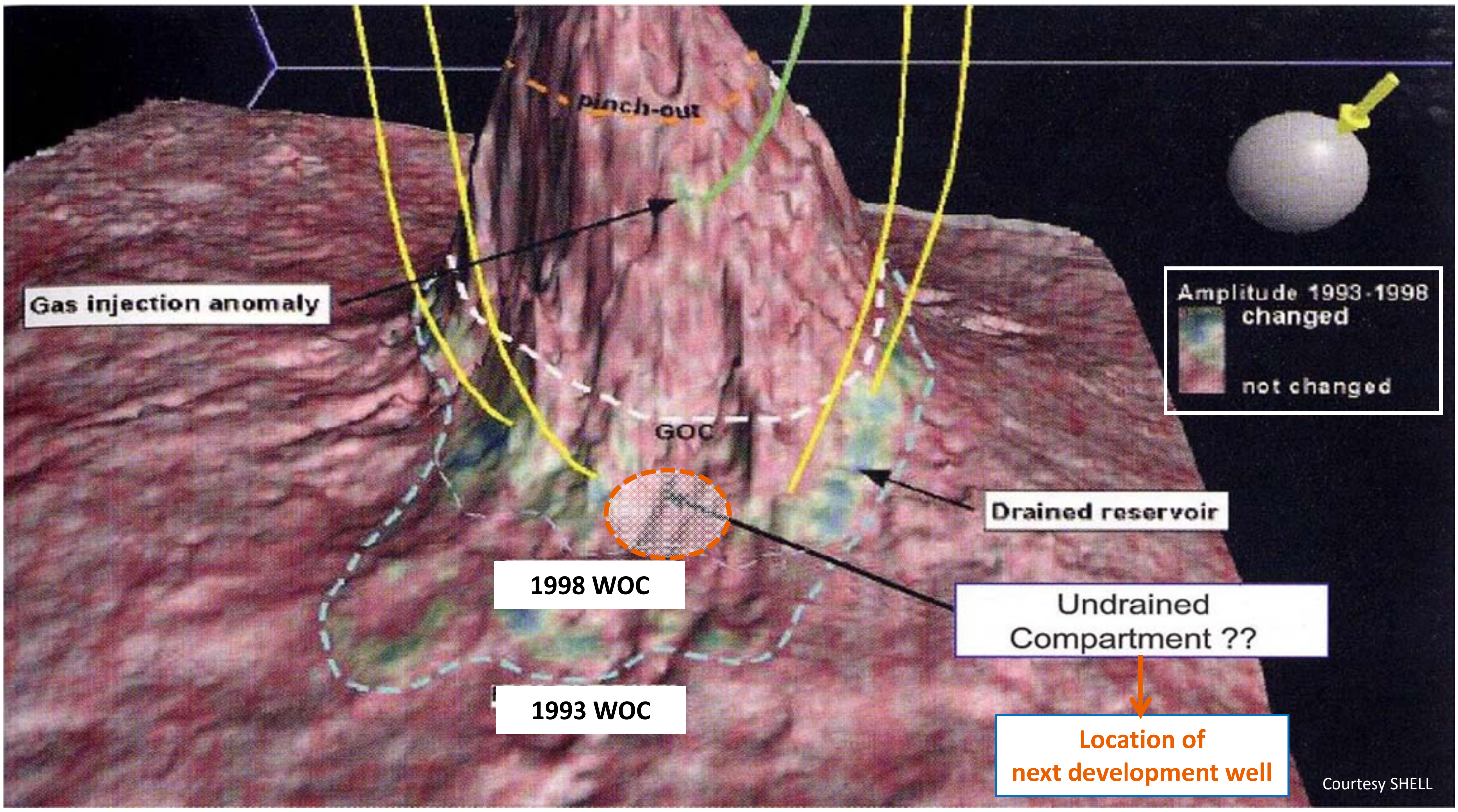
- **Principle**
  - Repeated seismic acquisition on same field
  - Seismic data “difference analysis”
- **Applications**
  - Identify fluid contact variations (vertical or lateral)
  - Track pore fluid saturation changes
  - Identify by-passed oil / in-fill drilling opportunities
  - Monitor performance of enhanced recovery (EOR) programs
  - Optimize production

4D seismic – Fluid level monitoring



4D seismic – Production optimization

Identification and analysis of differences between two surveys (1993-1998)



4D seismic: monitoring of production & reservoir sweeping → development well positioning

Geophysics in Exploration-Production - Key points - 1/2

- **Seismic provides an image of the subsurface (geometry) that is used (along with other data) to identify possible hydrocarbons accumulations (structures)**
- **Seismic data interpretation results are used to build models (both geological and reservoir) that summarize what can be understood at a given time**
- **Seismic models are validated (geologically) only by drilling (sampling "ground truth")**
- **Data gathering during development drilling, together with seismic information, allow models (both static and/or dynamic) to evolve**
- **4D seismic allows to monitor the evolution of a producing field (water injection, sweep efficiency,…) by comparing seismic images taken over time**

Geophysics in Exploration-Production - Key points - 2/2

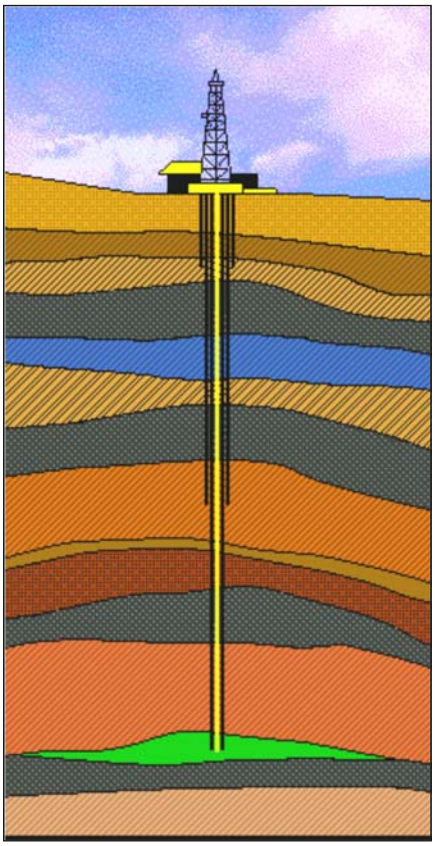
- **Geophysics is applied at each step of Exploration**
  - General exploration (screening)
  - Detailed exploration (prospect-focused)
  - "Wildcat" exploration well positioning
  - Delineation well positioning (appraisal)
- **Geophysics is also used in Production**
  - Development well positioning
  - EOR monitoring (4D seismic)
- **Geophysics is even used in Drilling**
  - Well path monitoring (geosteering)

Exploration tools & techniques

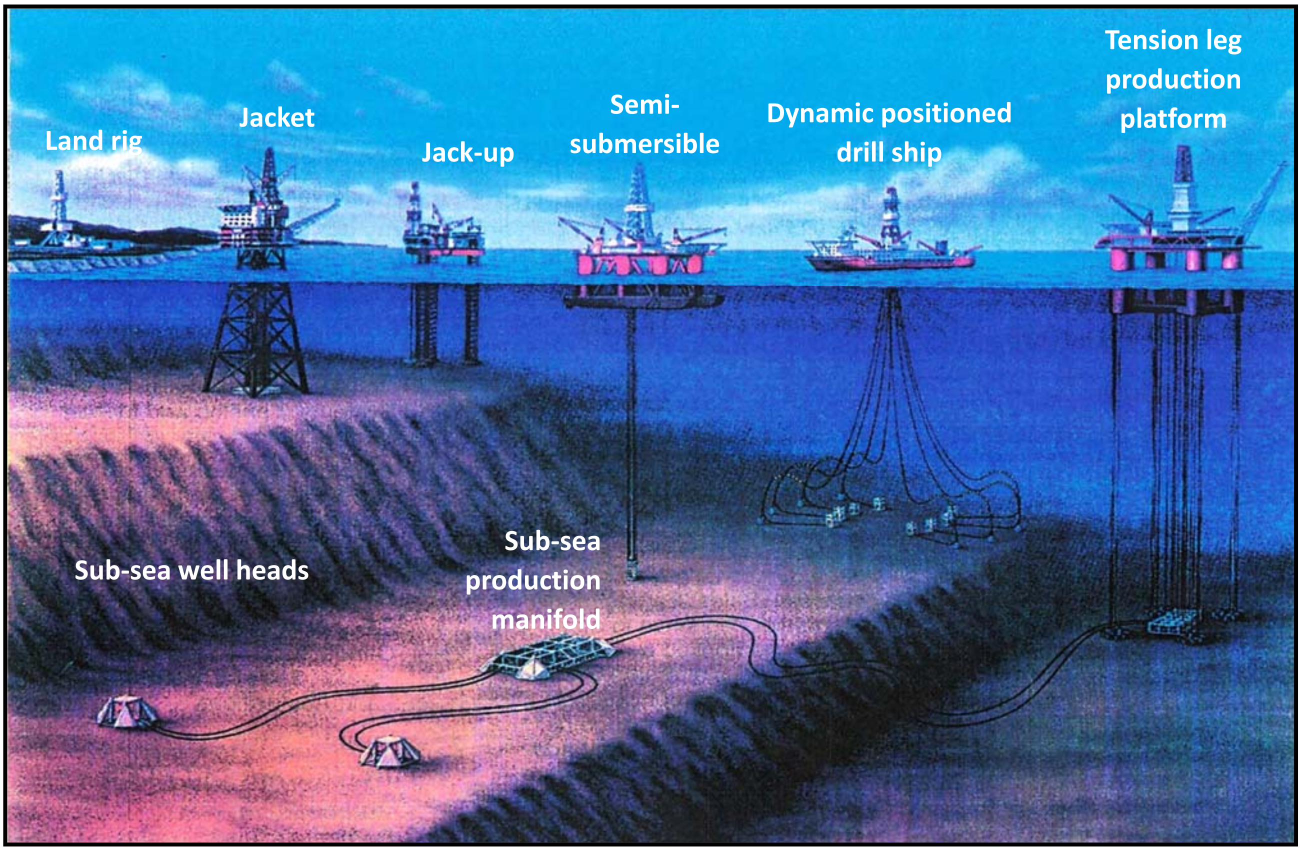
- **Operations geology**
  - Drilling (Reminder)
  - Completion (Reminder)
  - Logging
    - Mud logging
    - Wireline logging
    - “Quick look” analysis
    - Formation sampling
    - Dynamic measurements

Functions of the wells

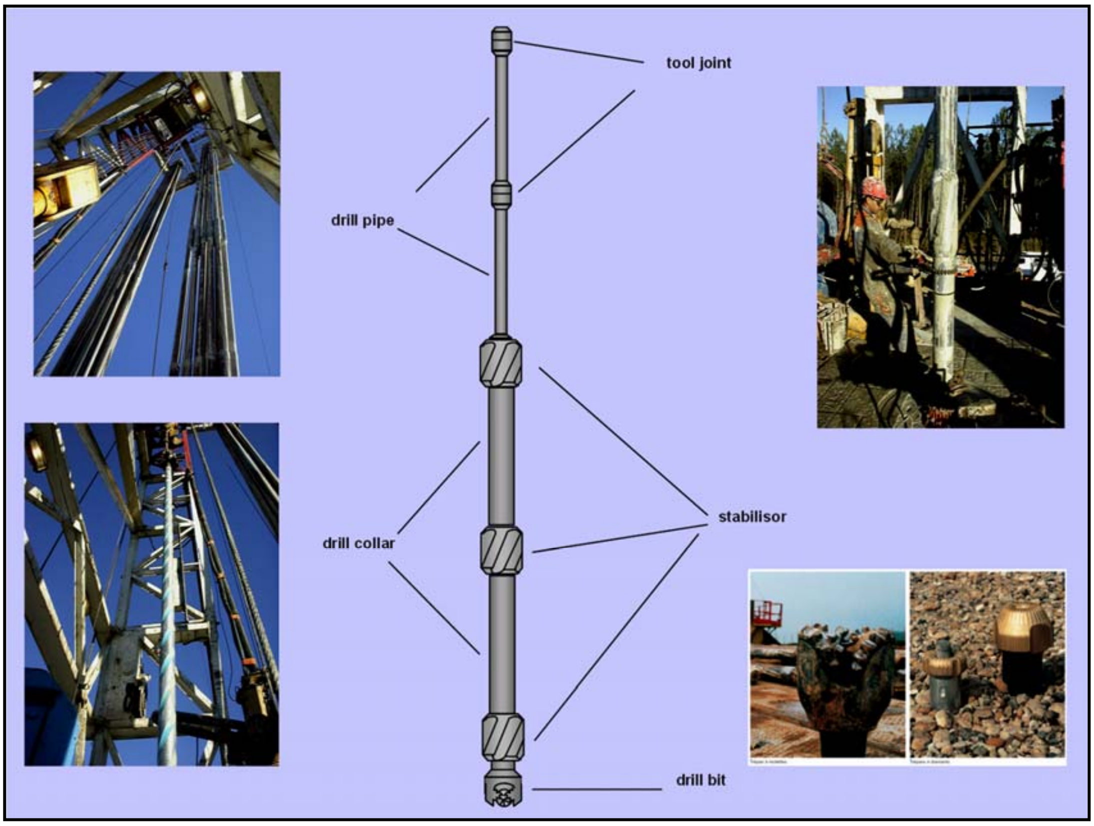
- **Allow access to the underground hydrocarbon reservoirs and to their properties .**
- **Ensure efficient communication between the reservoir and the well’s interior.**
- **Conduit to bring safely and efficiently hydrocarbons to surface .**
- **Allow the control of the high pressure hydrocarbon production.**
- **Allow well interventions to optimize hydrocarbon production during reservoir exploitation**



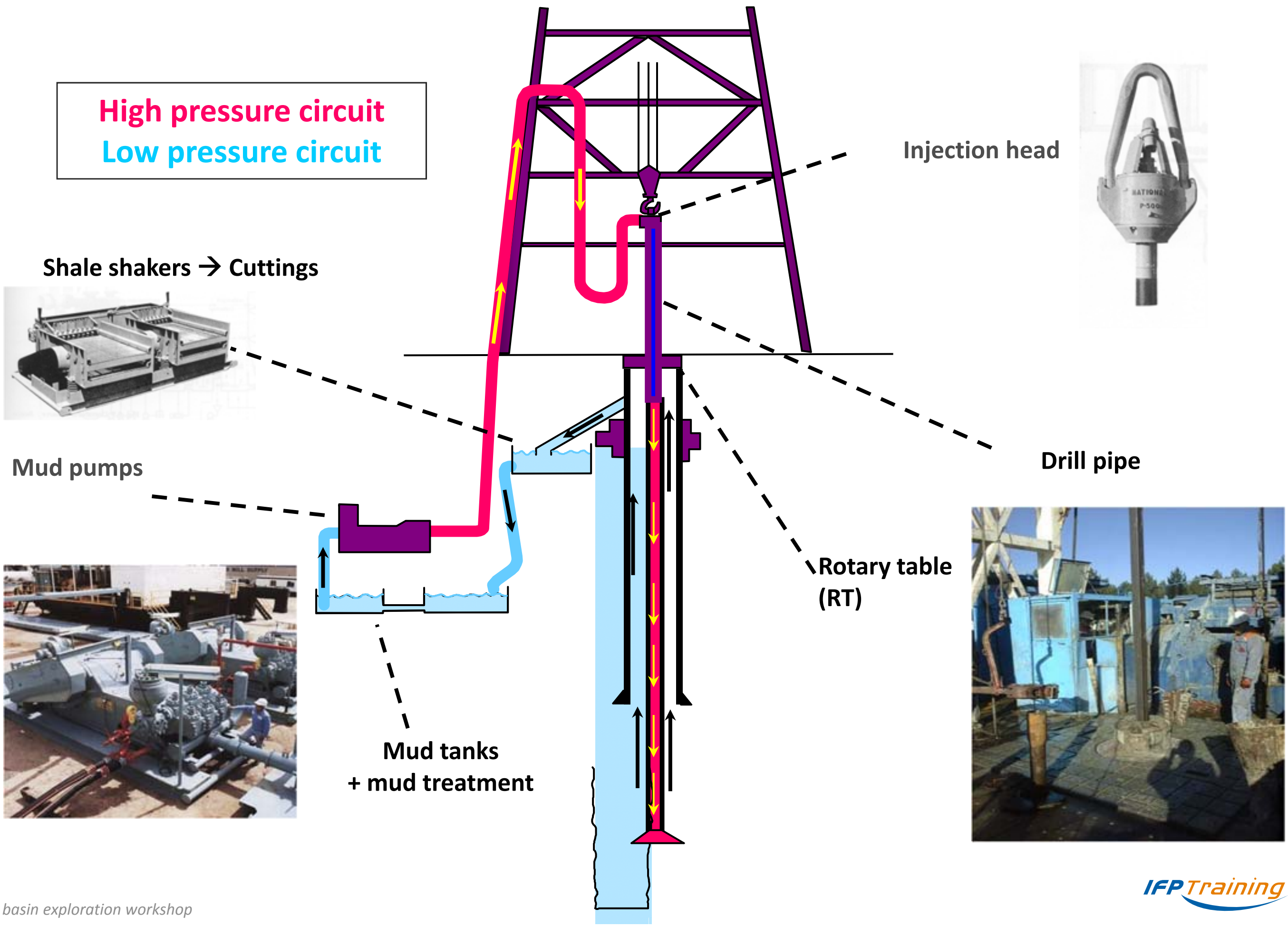
Different types of drilling rigs



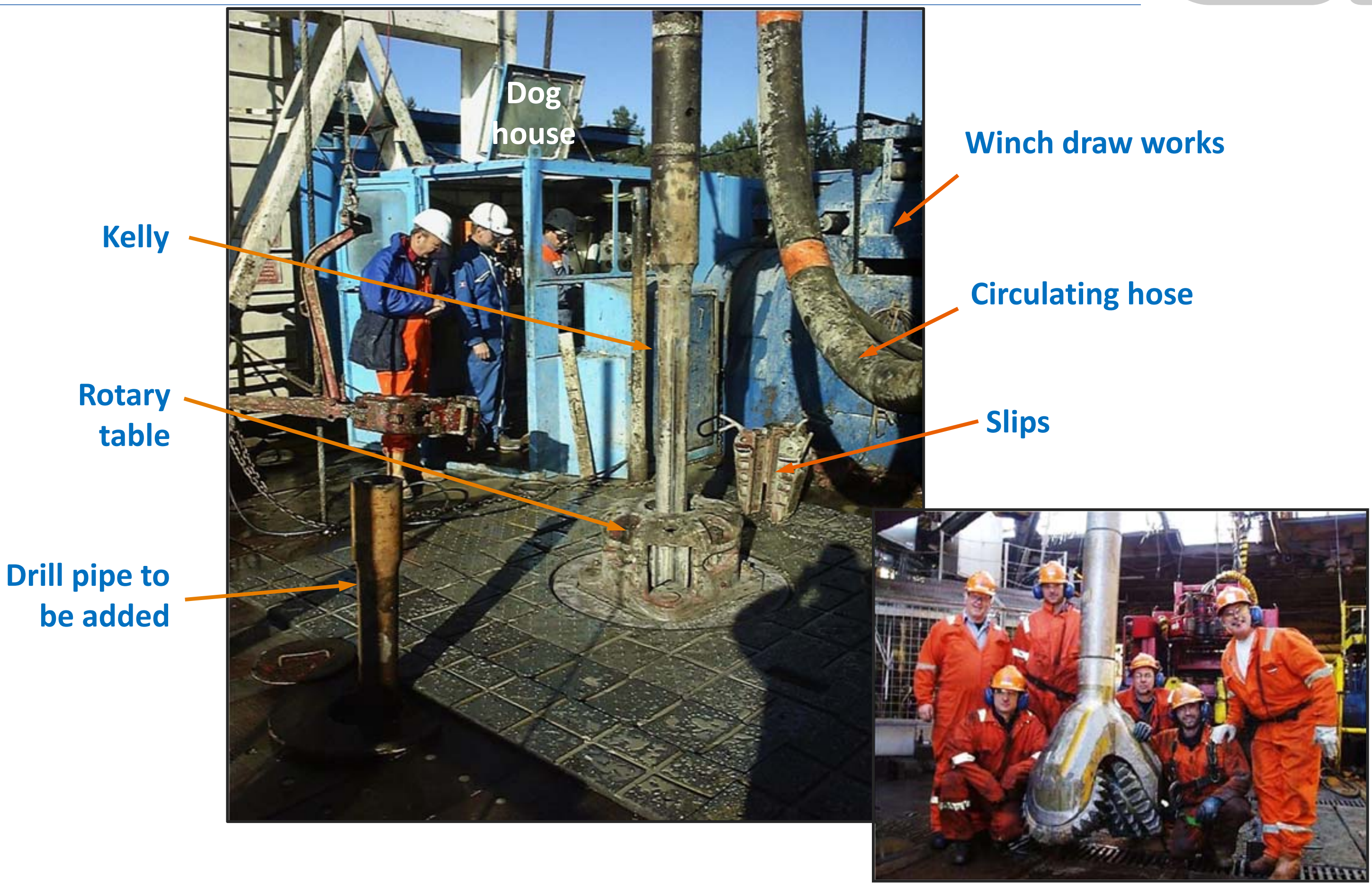
Drill string & drill bits



Mud circuit - Cuttings collection

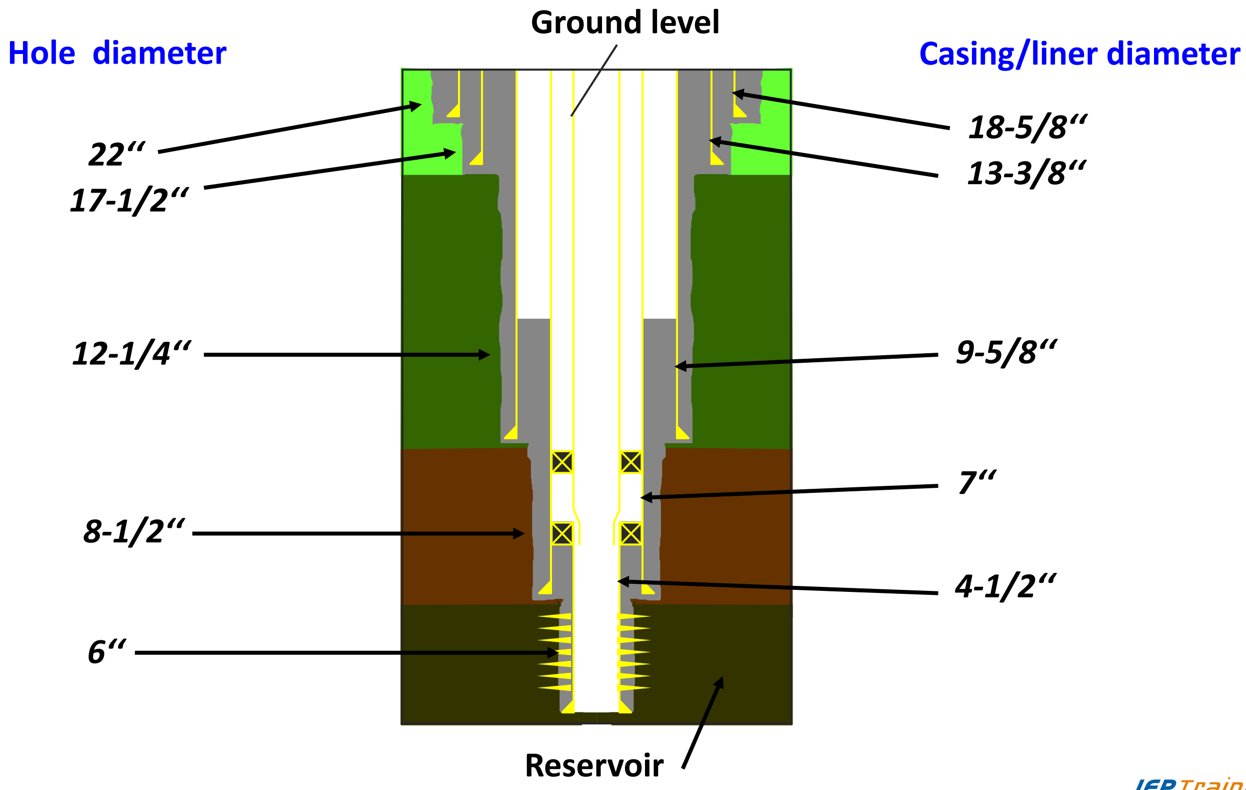


Drill floor



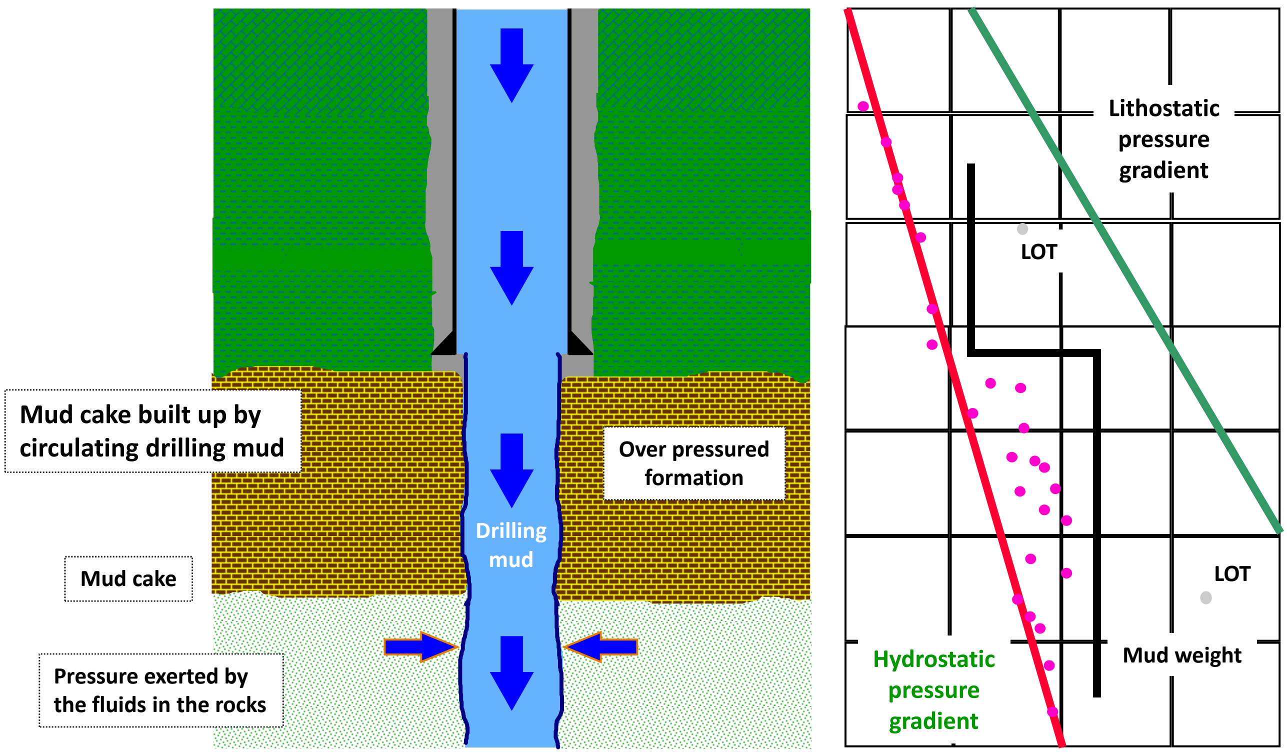
Well design

Bore-hole and casing diameters



Mud pressure in a well

Reservoir pressure and mud weight



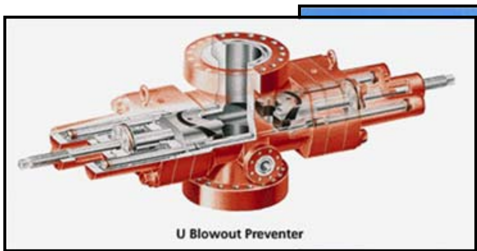
Exploration tools & techniques

▶ Operations geology

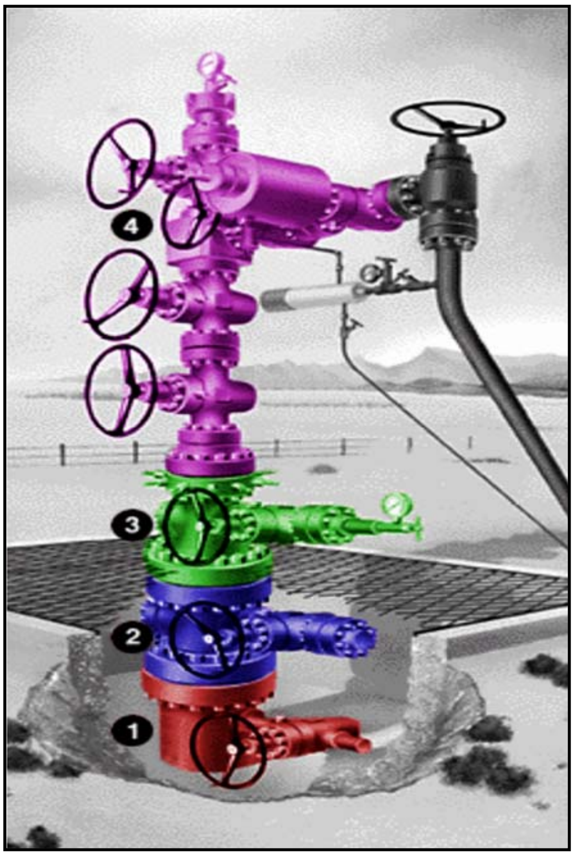
- Drilling (Reminder)
- Completion (Reminder)
- Logging
  - Mud logging
  - Wireline logging
  - “Quick look” analysis
  - Formation sampling
  - Dynamic measurements

Completion: well head equipment

Wellhead: BOP and X-mas tree

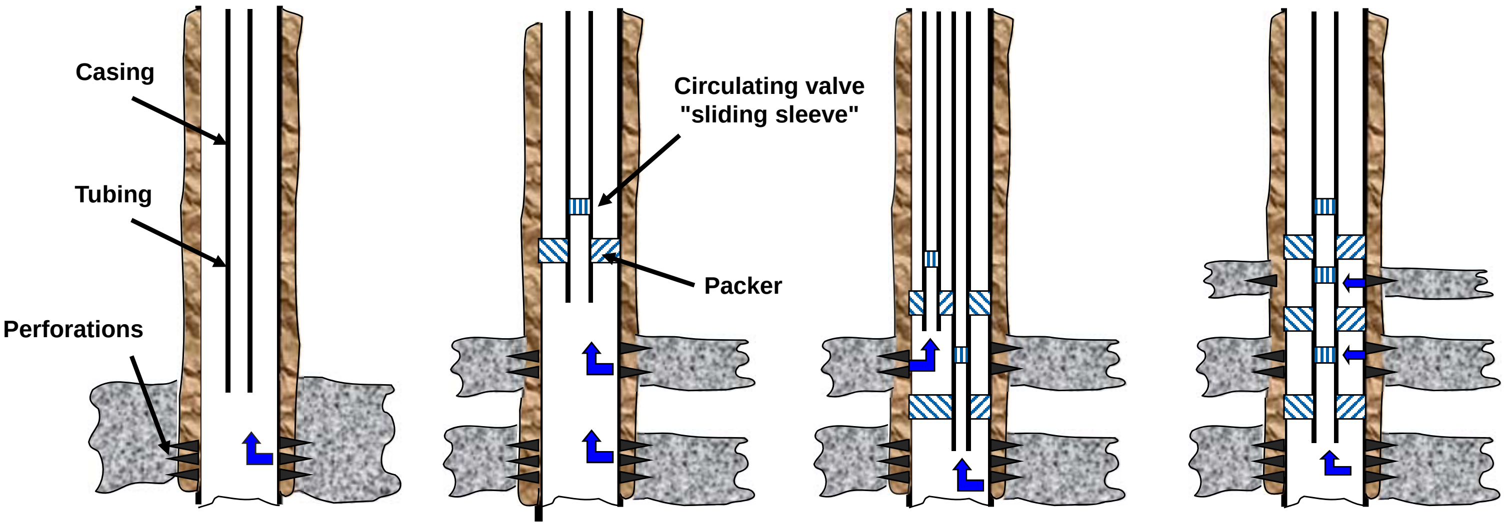


BOP: blow-out preventer



Blow-out prevention

Well completion types



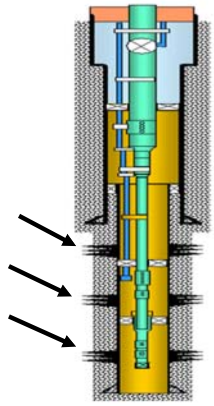
Standard completions

Dual completion

Selective completion

Perforations

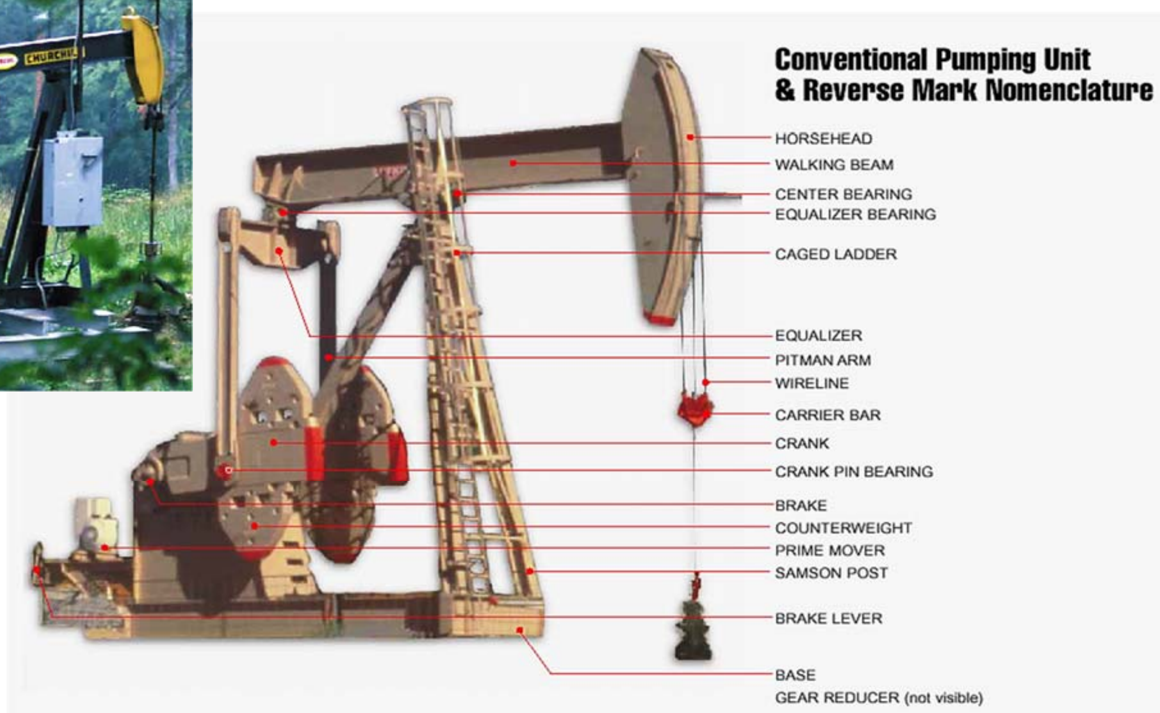
- **Perforations with overbalanced pressure before running completion:**
  - Large multidirectional cannons
  - Can damage the reservoir



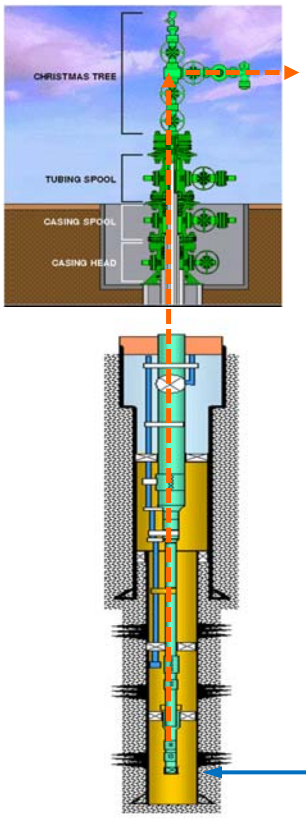
- **Perforations with underbalanced pressure and completion in place (TCP):**
  - Minimize reservoir damage
  - Smaller cannons

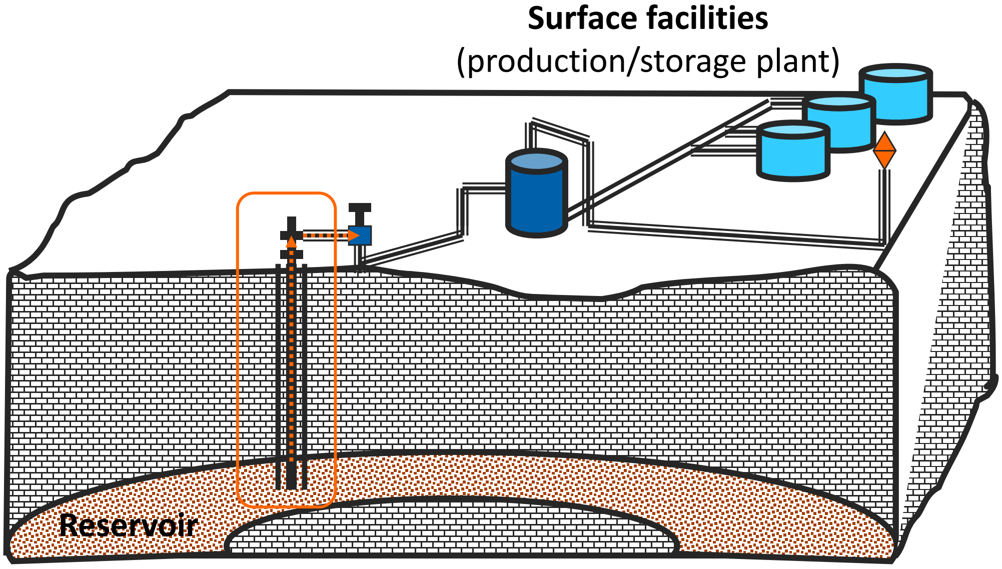
Well activation

Sucker road (« horse-head ») pump



Completion and production





Completion is the **link** between the **borehole** and **surface facilities**

Exploration tools & techniques

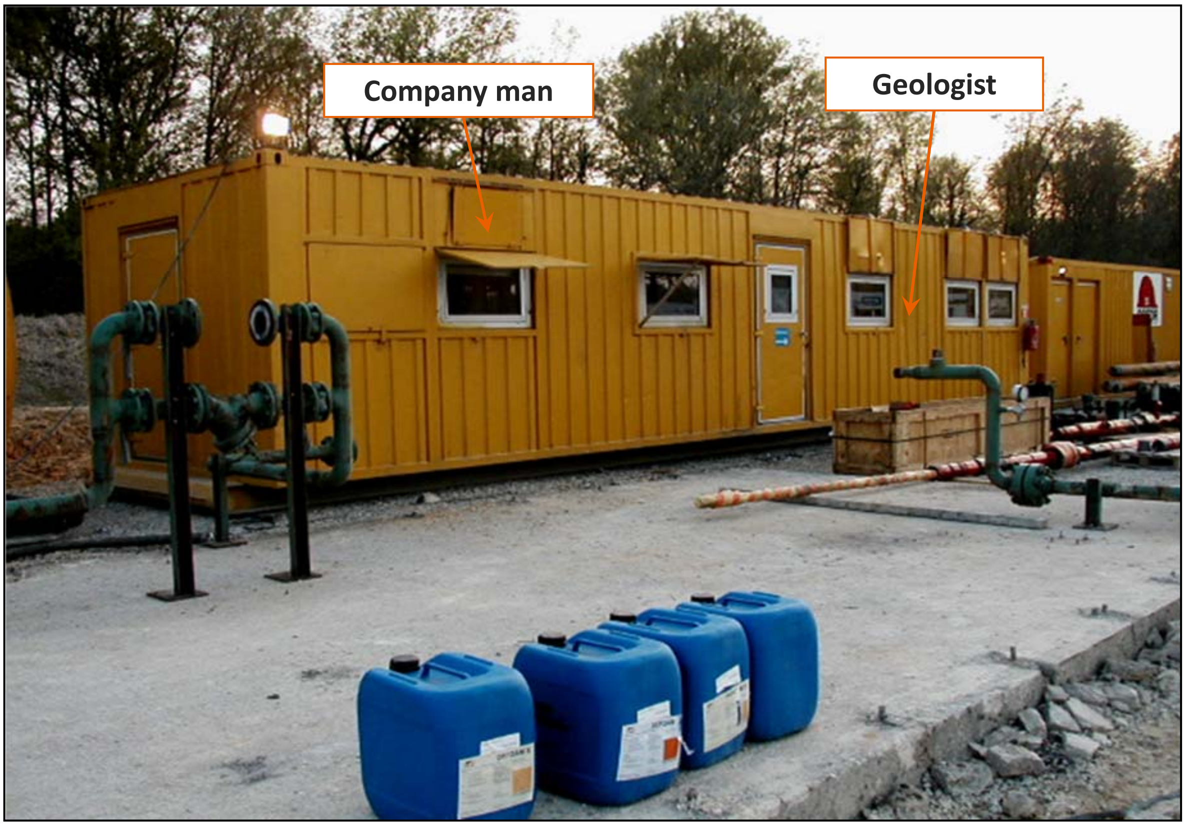
- **Operations geology**
  - Drilling (Reminder)
  - Completion (Reminder)
  - Logging
    - Mud logging
    - Wireline logging
    - “Quick look” analysis
    - Formation sampling
    - Dynamic measurements

Well logging: definitions

Well monitoring

- **Recording of one parameter (or more) versus a specific criterium or another precise parameter**
- **The response of this measurement is represented with a continuous curve (log)**
- **Three types of logs:**
  - **Instantaneous (mud logs):** recording of all parameters related to the well (mechanical, physical, chemical, geological,…) during the drilling phase – i.e. well monitoring
  - **Lagged (wireline logs):** recording of formations characteristics after the drilling phase, in the borehole, with electrical tools
  - **MWD/LWD:** measurement/logging while drilling record characteristics of drilled formations, like wireline logs, but in real time (tools on drilling string)

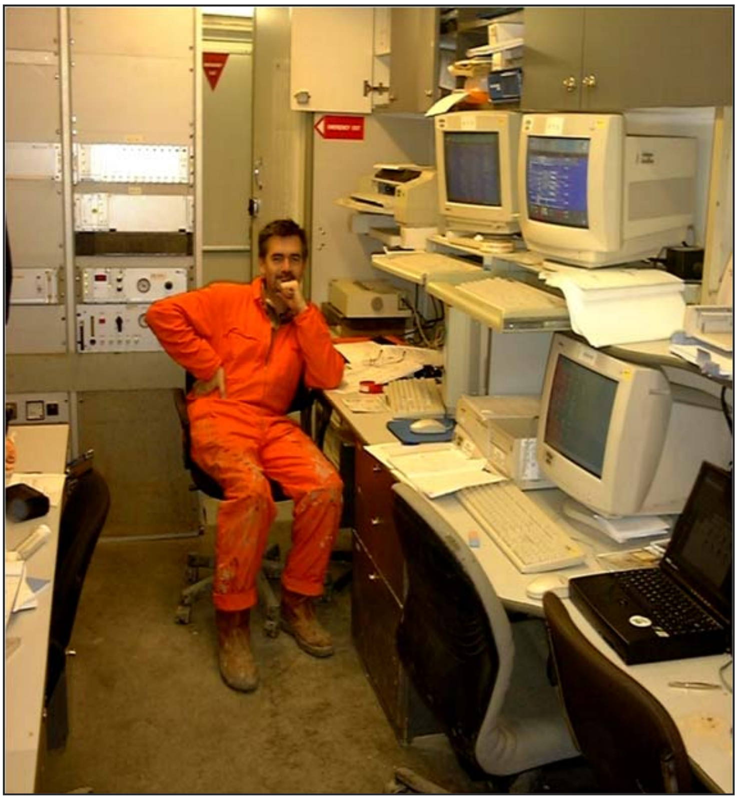
Wellsite geologist's cabin



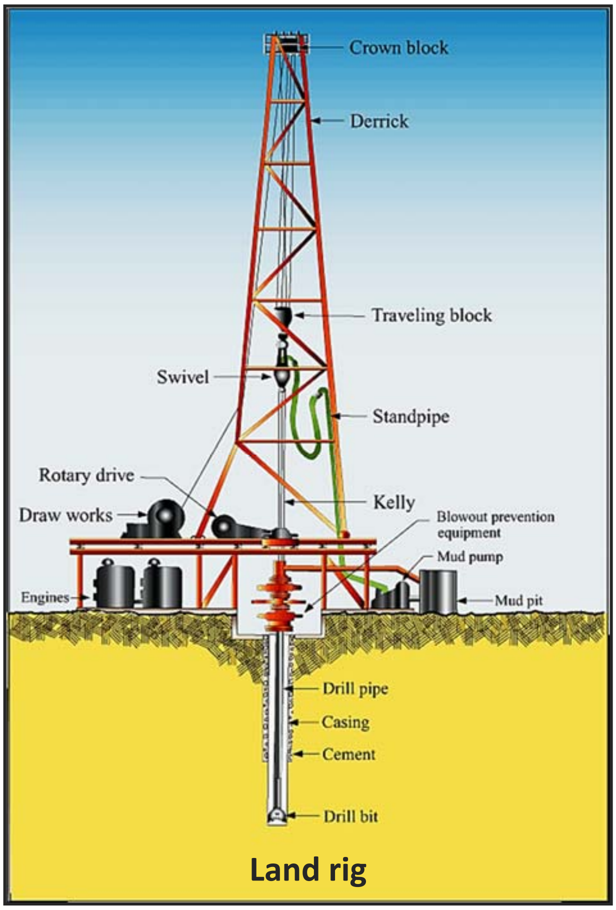
Mud logging unit

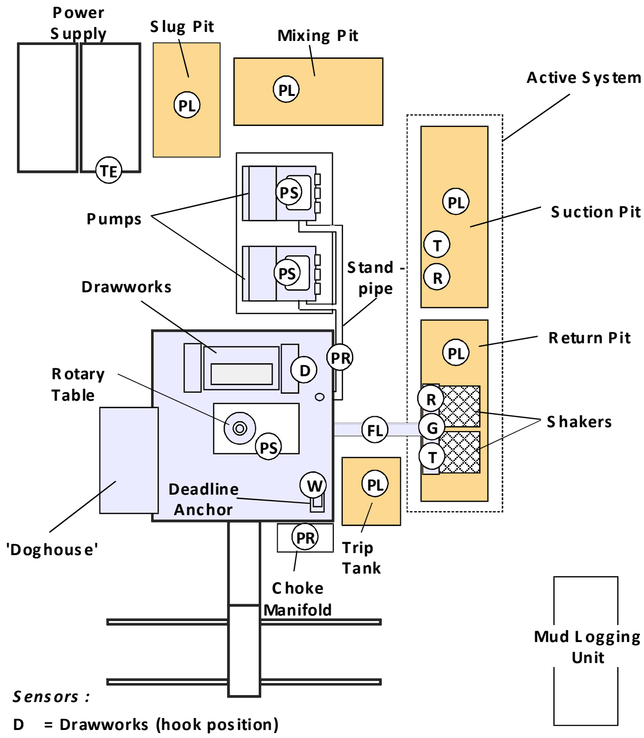
Geology side

Data management side



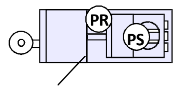
Sensors on rig





Sensors :

D = Drawworks (hook position)
FL = Mudflow (paddle)
G = Degasser
L = Pit levels
PR = Pressure
PS = Proximity Sensor (pumps / RPM)
R = Resistivity
T = Temperature
TE = Electric Torque
W = Weight on Hook



Cement Unit

Instantaneous parameter monitoring

- **Hook height**
- **Weight on hook** (WOH)
- **RPM**
- **Torque**
- **Injection pressure** (SPP)
- **Well head pressure** (annular pressure)
- **Pump strokes**
- **Mud pit level**
- **Mud parameters** *(see next slide)*

Lagged parameter monitoring

- **Gas in mud**
  - Hydrocarbons: C1 → C5
  - Hydrogen sulfide (H_2S)
  - CO_2 (optional)
  - H_2 (optional)
- **Mud parameters out**
  - Density
  - Temperature
  - Conductivity
  - Mud flow out
- **Formation**
  - Lithology (cuttings %)
  - Calcimetry

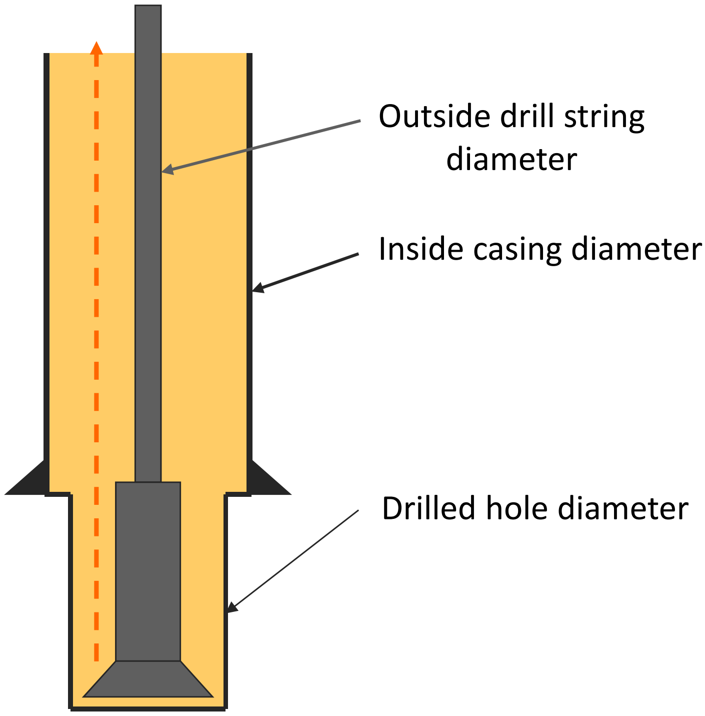
Mud functions

- **Multiple**
  - Clean the well
  - Keep cuttings in suspension
  - Lubricate the bit
  - Maintain the walls of the well
  - Prevent eruption (kick off)
- **Characteristics of the mud**
  - Mud = fluid (water, oil) + solid particles
  - Dynamic equilibrium at well/formation interface
  - Mud Pressure > Formation Pressure
- **Phenomenon of invasion (flushing) in reservoirs**
  - Invasion: mud filtrate in the formation's porous network
  - Accumulation of particles in front of the reservoir → mud cake

Mud - Cuttings lag-time

Lagtime = ellapsed time for the mud to reach surface from well bottom

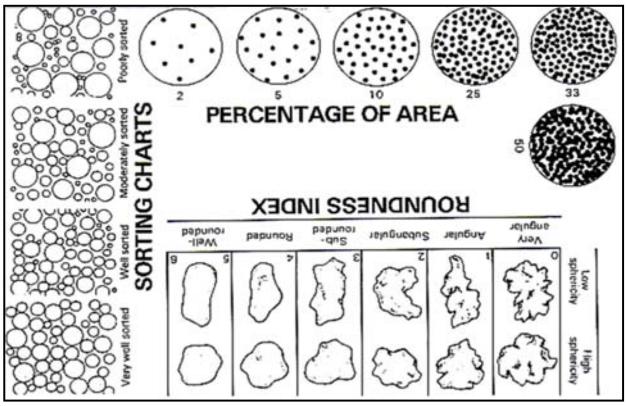
- Lagtime
  - cuttings rising from formation to surface
- Cuttings mix - main causes:
  - Recycling of finest particles
  - Improper cleaning of mud pit
  - Quality (accuracy) of sampling
  - Preparation, handling of samples
- Sampling rate (frequency)
- Sample volume
- Special cases
  - Presence of plugging agents
  - Drilling fluid: foam or air



Lagtime = Annular volume (m^3) / Pump output (m^3/min.)

Cuttings - Collection on shale shakers

Cuttings - Description

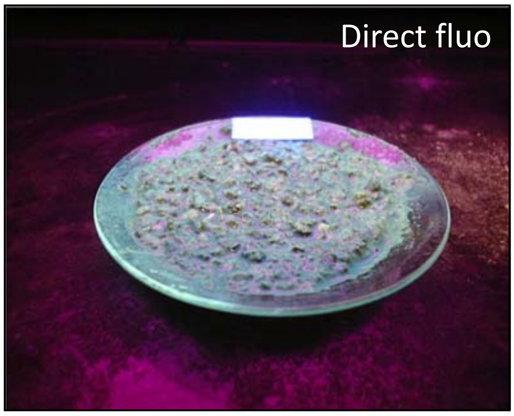


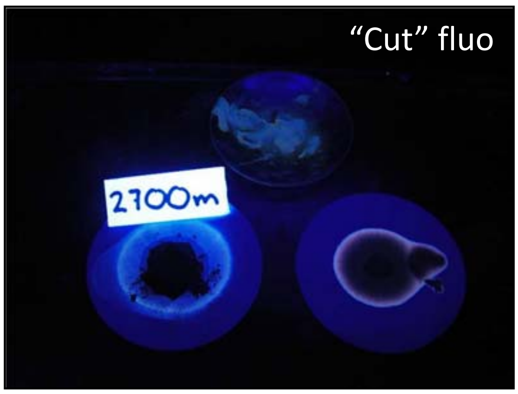
Example of description:

SANDSTONE, gray-brown, friable, medium-coarse grained, sub-rounded, moderately sorted, poor calcareous cement, glauconitic, fair yellowish direct fluorescence, strong yellow cut fluorescence.

Oil shows detection

- **Direct or « cut » fluorescence**
  - Presence of hydrocarbons
  - Active (gas or liquids)
  - Fossil (bitumen or asphalt)
- **False fluorescence**
  - Drilling oil (lubrication)
  - Exhaust gas (engines)
  - Contaminated mud or equipment (tanks, pits,…)





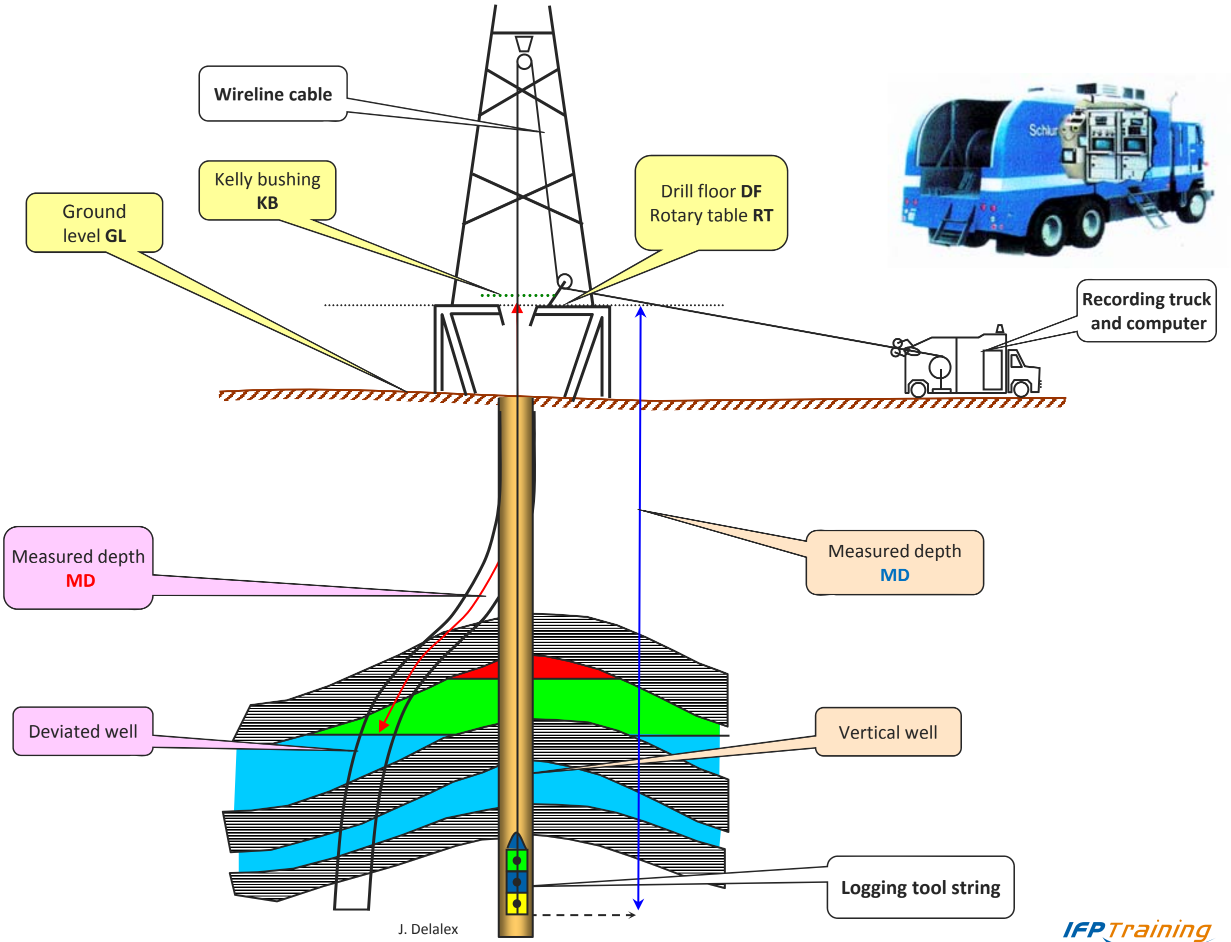
Exploration tools & techniques

- **Operations geology**
  - Drilling (Reminder)
  - Completion (Reminder)
  - Logging
    - Mud logging
    - Wireline logging
    - “Quick look” analysis
    - Formation sampling
    - Dynamic measurements

Wireline logging

- Recording of **physical phenomena** linked with petrophysical characteristics of drilled formations and fluids in place.
- Recording **after the drilling phase**, every 15 cm down to 3 cm (1 foot > 1 inch)
- Logs provide a **continuous image** of the subsurface, in situ, detailed information but limited to the wellbore neighborhood (less than 1 m diameter around the hole)
- **Three types of logs:**
  - Well logs for geologists & geophysicists for formation and fluid evaluation and characterization and quatification
  - Well logs for drillers that give technical information (e.g. cementation quality, sticking point detection for fishing, etc.)
  - Well logs for production engineers to analyze all phenomena linked to the fluids and their displacement

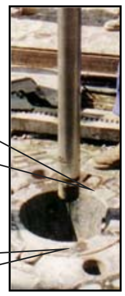
Onshore wireline logging



Wireline logging operations

Caliper calibration

Rig site and logging truck



String bottom

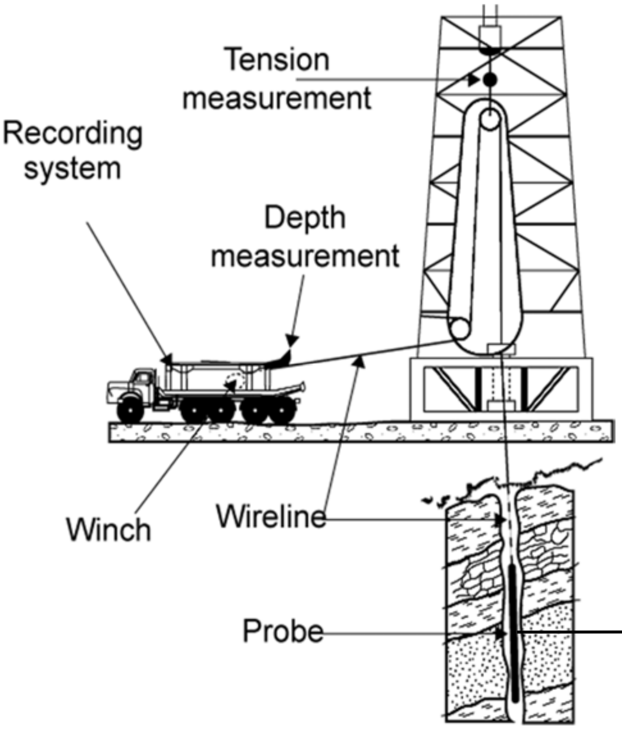
Kelly Bushing KB

Rotating during drilling

Depth measurement

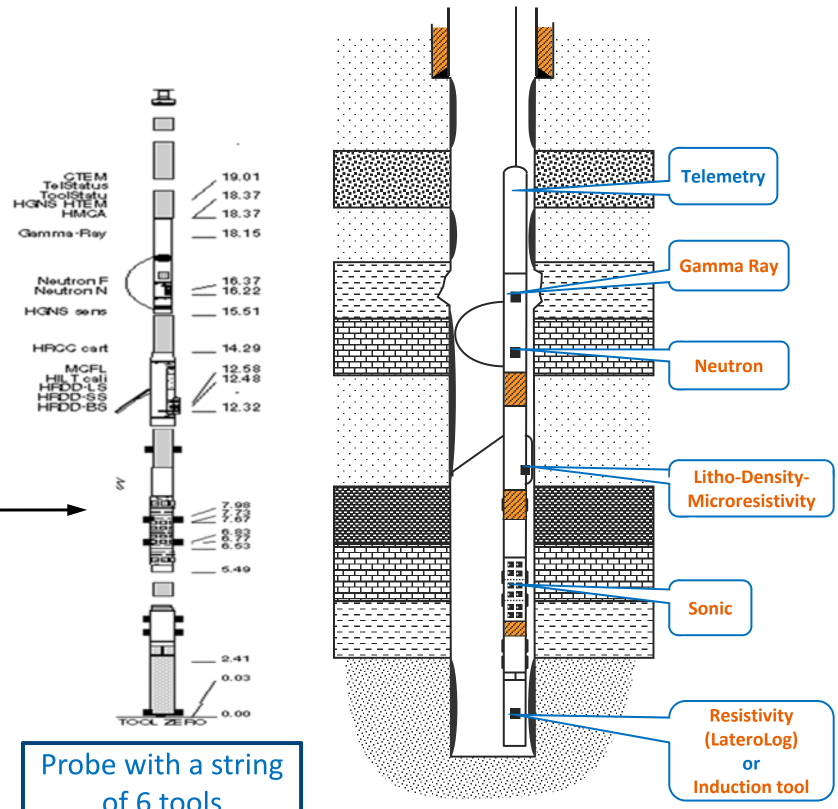
Logging tool string

Tool combinations (strings)



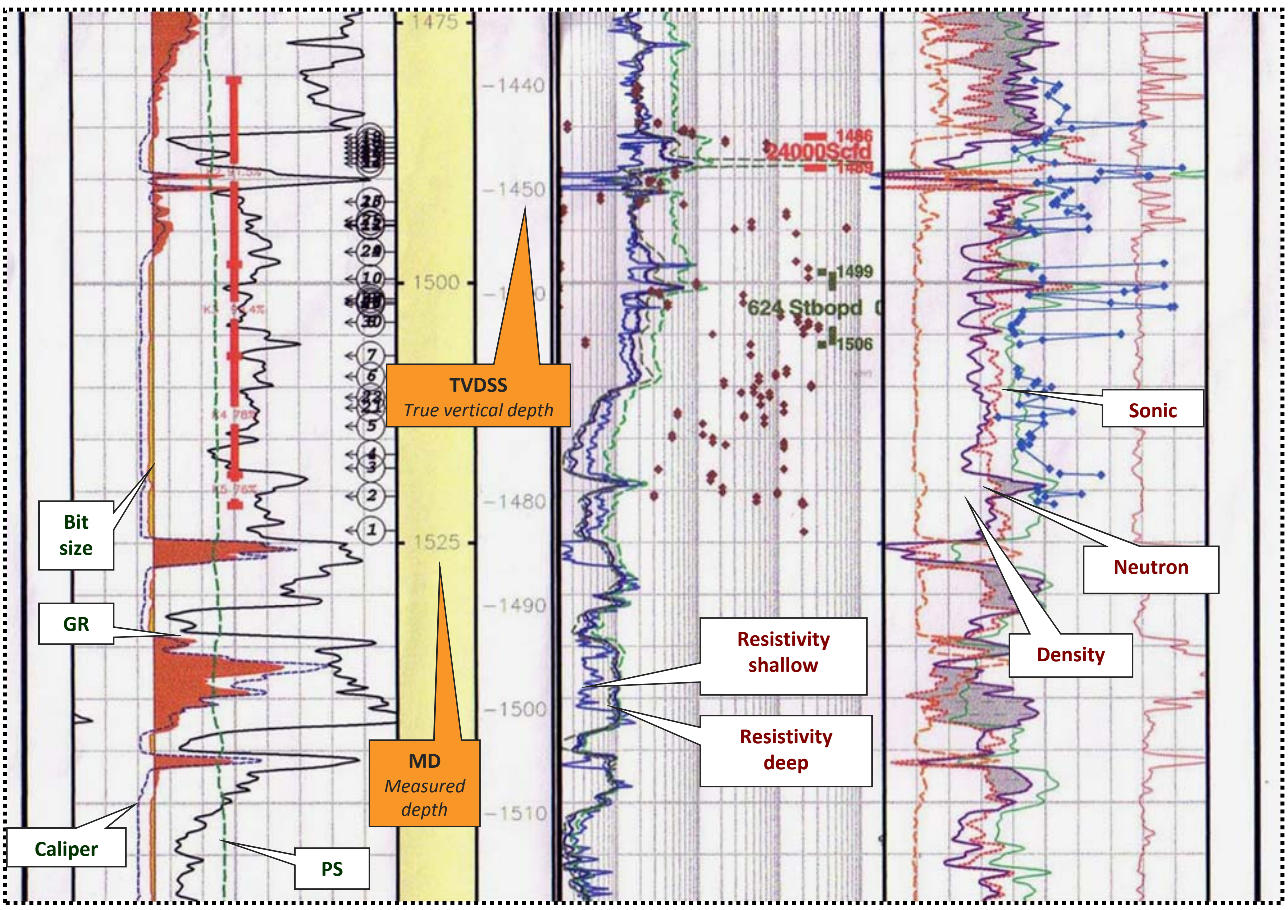
Suite (string) of logging tools

(Platform Express – PEX - Schlumberger)



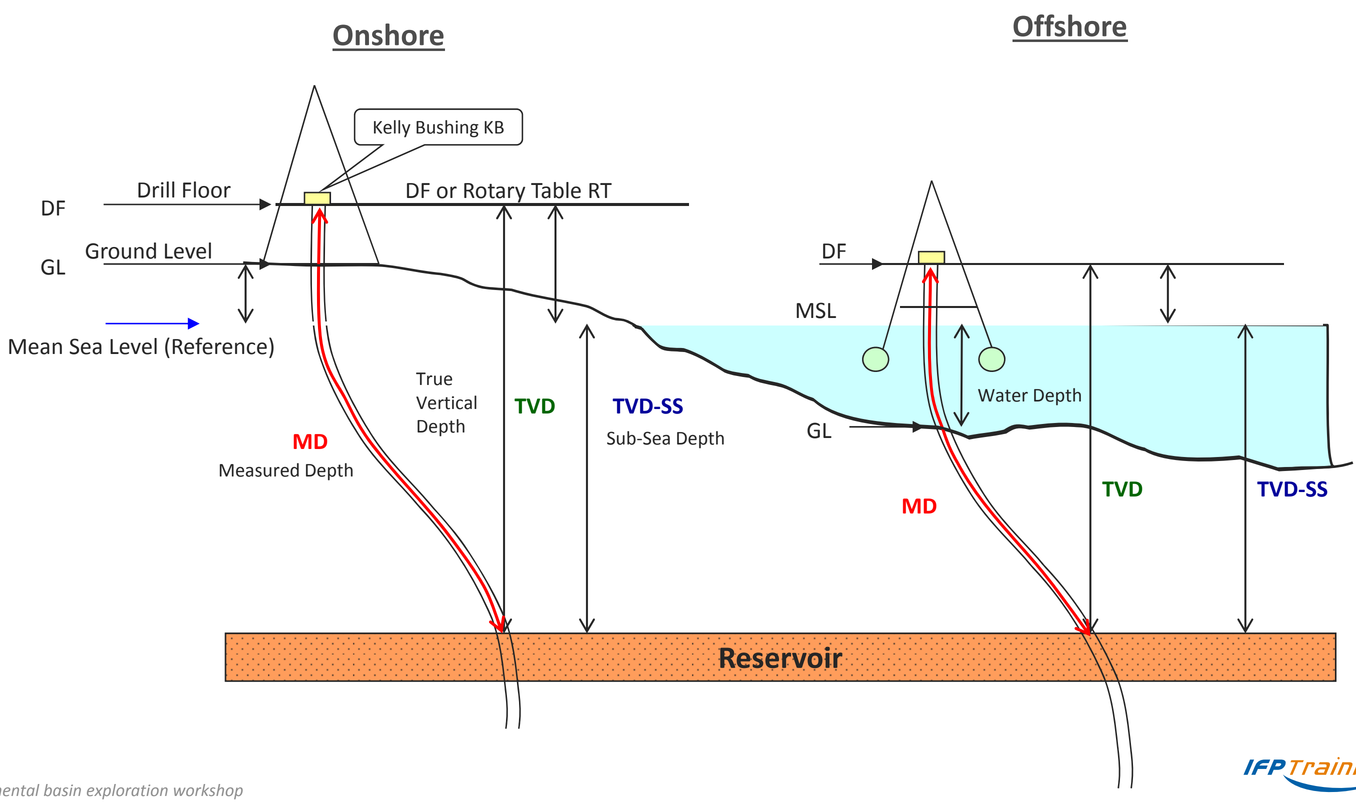
Probe with a string of 6 tools

Raw wireline log curves



Depths and references

MD – TVD – TVDSS – KB – RT – DF – MSL



Most commonly used wireline logs

- **CALIPER** — **Well-bore diameter**
  quality control of other logs: diameter, volume, mudcake, …
- **GAMMA RAY (GR)** — **Natural radioactivity**
  stratigraphy, shaliness, reservoirs, correlations, …
- **SPONTANEOUS POTENTIAL (SP)** — **Natural currents**
  stratigraphy, shaliness, reservoirs, correlations, water resistivity, …
- **RESISTIVITY** (Laterolog, Induction, Microlog,…) — **Activated currents**
  hydrocarbons, saturations, fluid invasion, …
- **NEUTRON (NPHI)** — **Activated radioactivity**
  porosity, lithology, oil/gas, …
- **DENSITY (RHOB)** — **Activated radioactivity**
  lithology, porosity, oil/gas, …
- **SONIC (DT)** — **Transit time**
  lithology, porosity, fluids, …
- **DIPMETER** — **Layer dip & boundaries**
  structural deformation, geometry, …
- **NMR**
- **etc.**

Wireline logging tools types

- **Natural phenomena recording**
  - Well diameter — **Caliper**
  - Natural radioactivity — **Gamma Ray**
  - Formation temperature — **Temperature**
- **Artificially stimulated phenomena recording**
  - Formation resistivityResistivity, — **Induction** → **Fluid**
  - Formation lithology & porosity — **Neutron, Density, Sonic** → **Rock**
- **Tools**
  - Source/receiver spacing
    - Depth of investigation
    - Vertical resolution
  - Centered in borehole or pressed against wellbore (pad)

→ Determination of both reservoir zones and fluid content

- Invasion (mud cake detection)
- Identification of fluids and respective saturations

Caliper

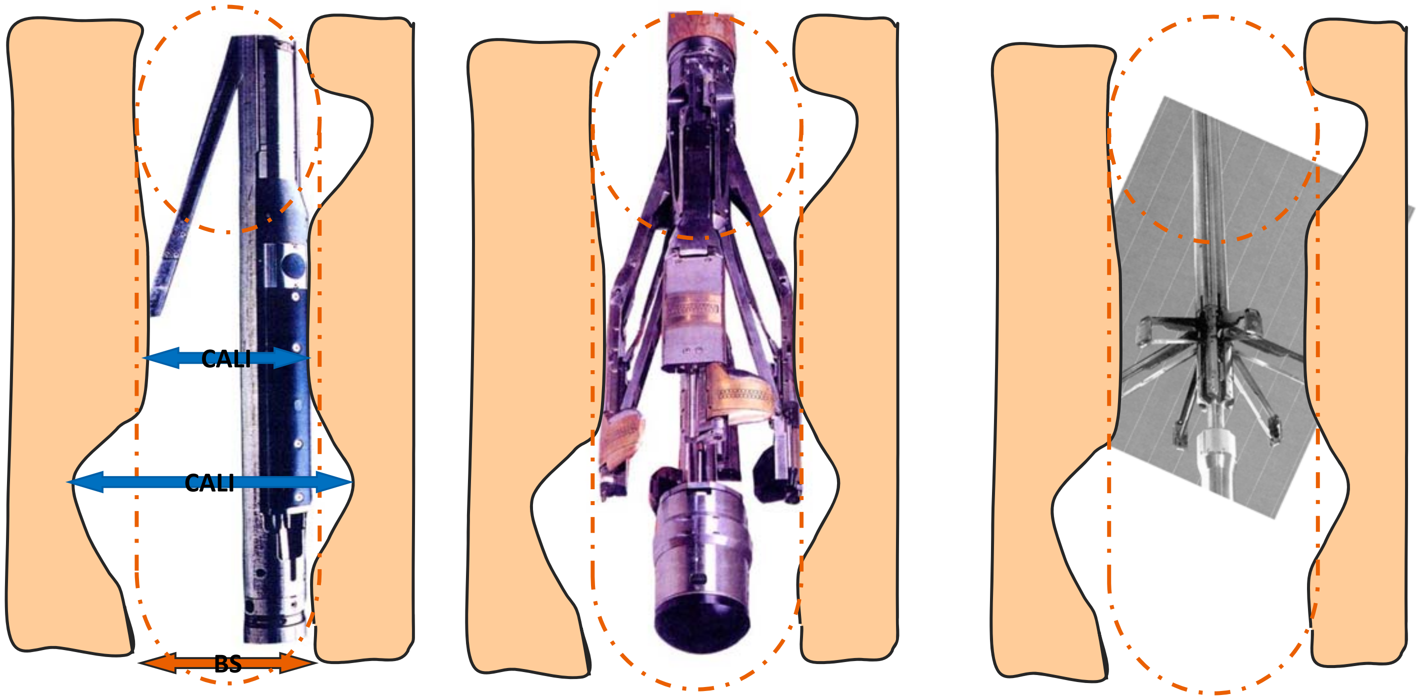
- **Measures effective diameter of borehole**
  - Two opposites arms
  - Four arms, two by two in diagonal
- **Measurement in constant drilling phase**
  - Comparison with bit size
  - Fluctuates around bit size values
- **Applications**
  - Potential mud cake location
  - Caves, irregularities in borehole walls

Types of calipers

Litho-density tool

Formation micro-imager

6-arm dipmeter - EMI

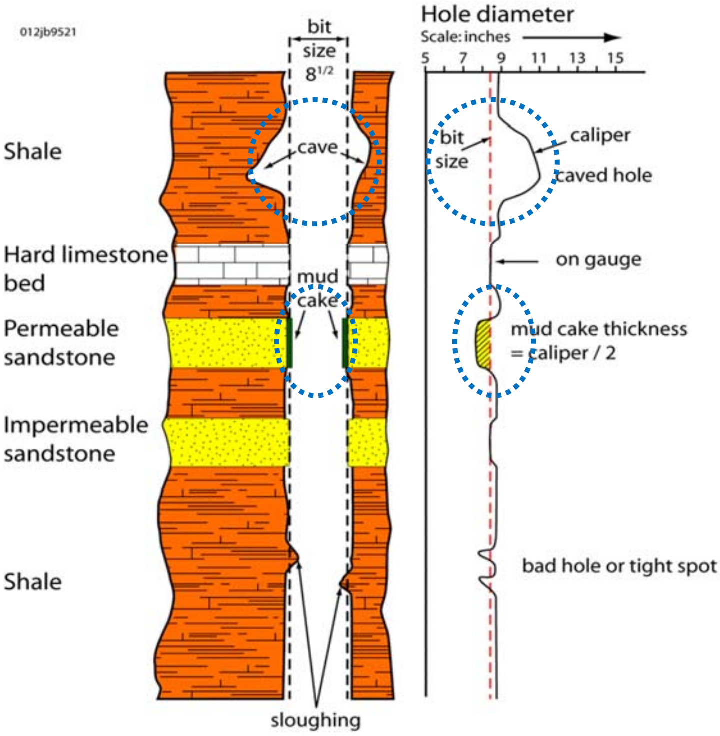


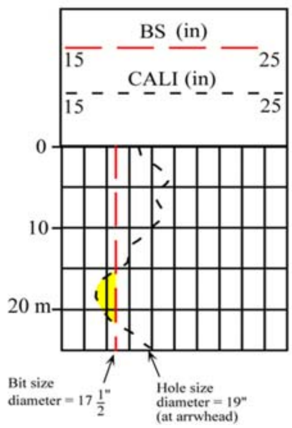
Excentered tool w/ 1 arm
→ 1 diameter value

Centered tool w/ 4 arms
→ 2 diameter values

Centered tool w/ 6 arms
→ 3 diameter values

Caliper results





Ø ↑ : Cave

Ø ↓ : Swell (mud cake)

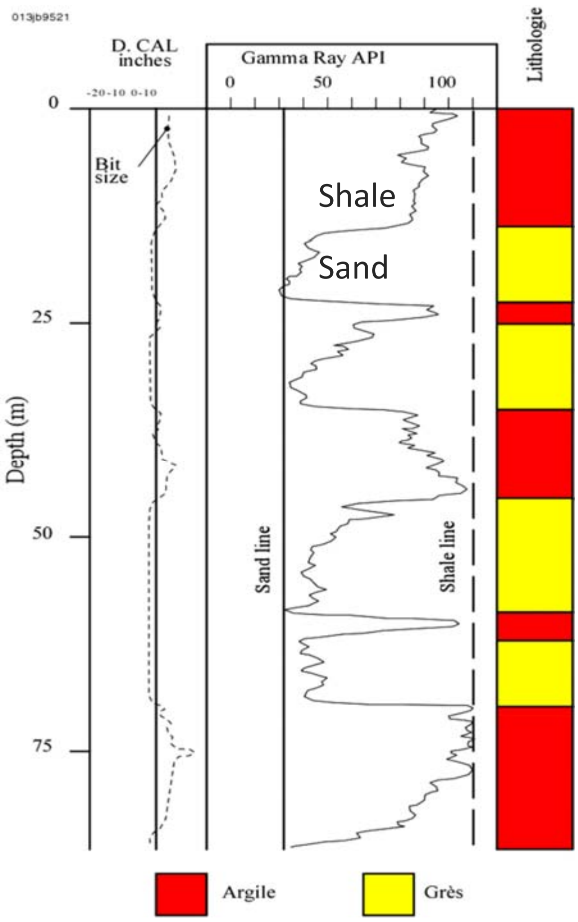
Gamma Ray

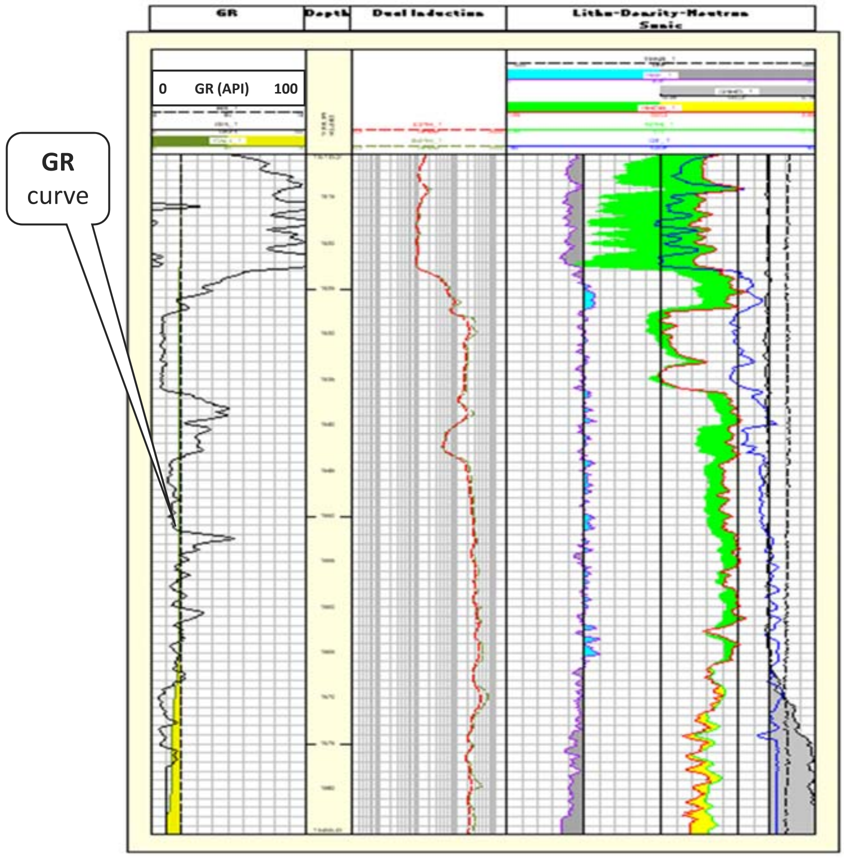
- **Measures natural radioactivity in rocks**
  - Radioactive elements : Thorium, Potassium, Uranium
  - Global GR or Spectral GR
- **Representation on log**
  - API unit : from 0 to 100 or 150
  - Recording on first track, linear scale
  - Increasing on the right
- **Applications**
  - Shales layers, shales content in reservoir
  - Correlation between wells,
  - Sedimentary bed boundaries …

GR - Natural radioactivity

- **K: Potassium**
  - Shales (illites)
  - Potassic evaporites
  - Potassic feldspars
  - Micas
  - Minerals with K
  - Mud with KCl
- **Th: Thorium**
  - Detritic shales
  - Minerals with Th (heavy minerals)
- **U: Uranium**
  - Shales (with organic matter)
  - Organic matter
  - Minerals with U

Example of GR log





Neutron tool

- **Measures number of hydrogen nuclei in formation**
  - Not located in the “conventional matrix” for reservoir
    - Sandstone, Limestone, Dolomite
  - Associated with fluids in porosity for reservoir formations
  - Gives an “apparent porosity”
- **Representation on log**
  - Porosity unit (pu): from 0 to 60 or -15 to + 45
  - Recording on linear scale
  - Increasing to the left
- **Applications**
  - Fluid content
  - Shale volume
  - Computation of porosity (true porosity in reservoir formation)

Density tool

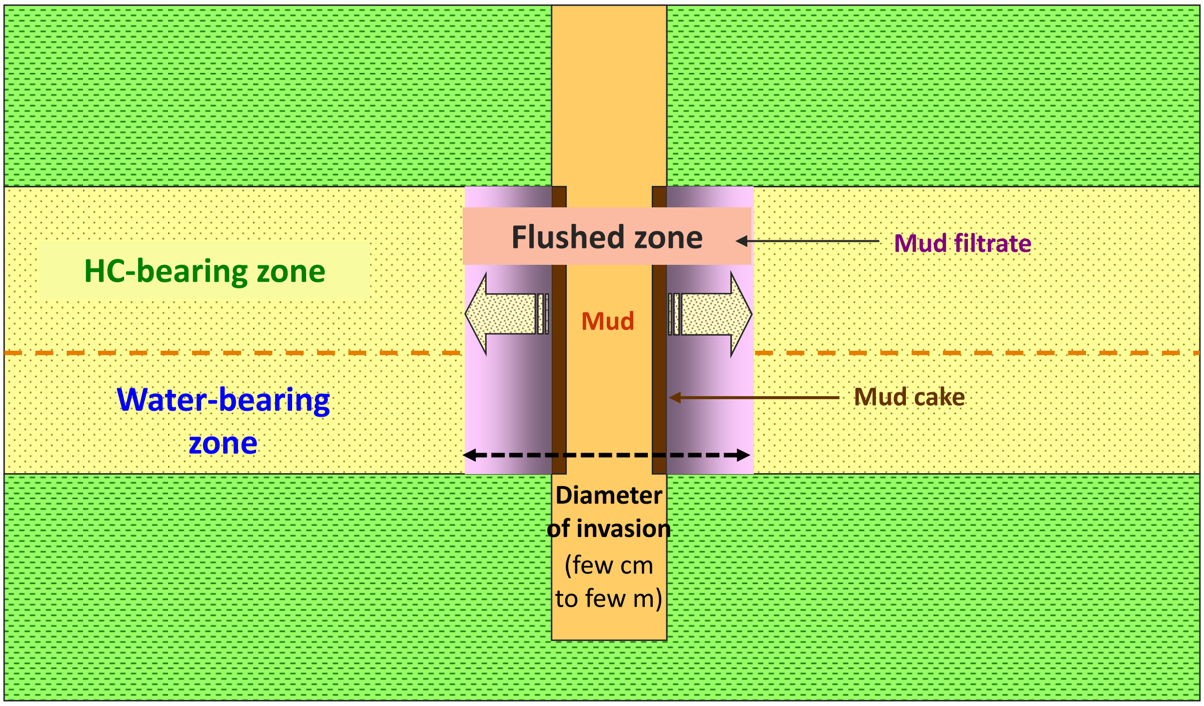
- **Measures the global density of a formation**
  - Compton effect (attenuation of gamma rays in formations)
  - Gives “apparent porosity”
- **Representation on log**
  - Density unit: g/cc
  - Recording on linear scale
  - Increasing to the right
- **Applications**
  - Fluid content
  - Shale volume
  - Computation of porosity (true porosity in reservoir formation)

Sonic tool

- **Measures propagation of acoustic waves in the formation**
  - Seismic refraction
  - Time delay in the formation between a reference spacing (Δt)
  - Provides interval velocities
- **Representation on log**
  - Unit: microsecond/feet
  - Recording on third track, linear scale
  - Increasing to the right
- **Applications**
  - Identification of lithologies
  - Computation of porosity (true porosity in reservoir formation)
  - Secondary porosity

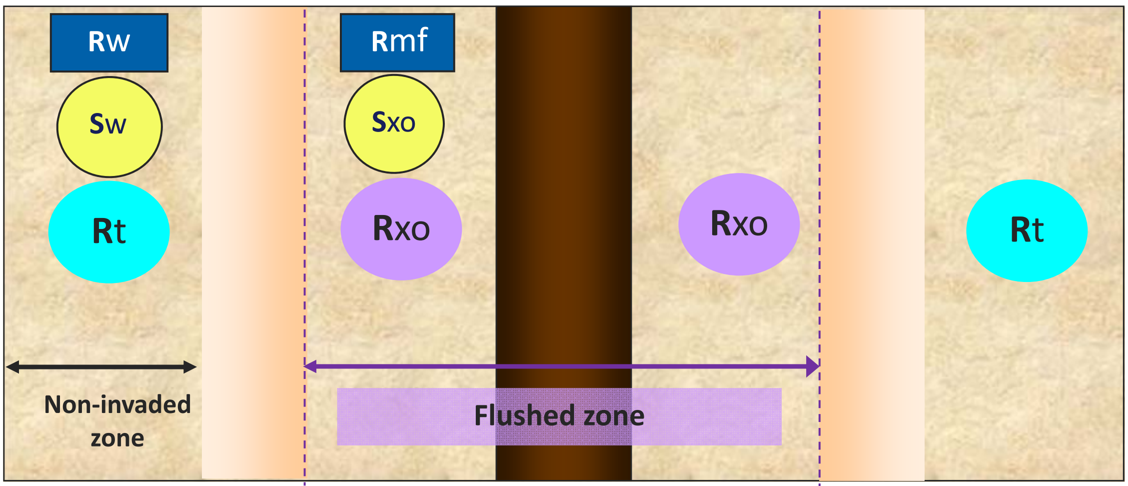
Formation invasion by mud filtrate (reservoir flushing)

Invasion phenomenon only occurs in reservoir zones (i.e. ϕ, K)



The mud filtrate (liquid) penetrates porous & permeable formations (i.e. reservoirs) until the cake (solid) gets thick enough to prevent from further flushing (i.e. invasion)

Resistivity and invasion



Rmf = Resistivity of mud filtrate

Rw = Resistivity of water in non-invaded (virgin) zone

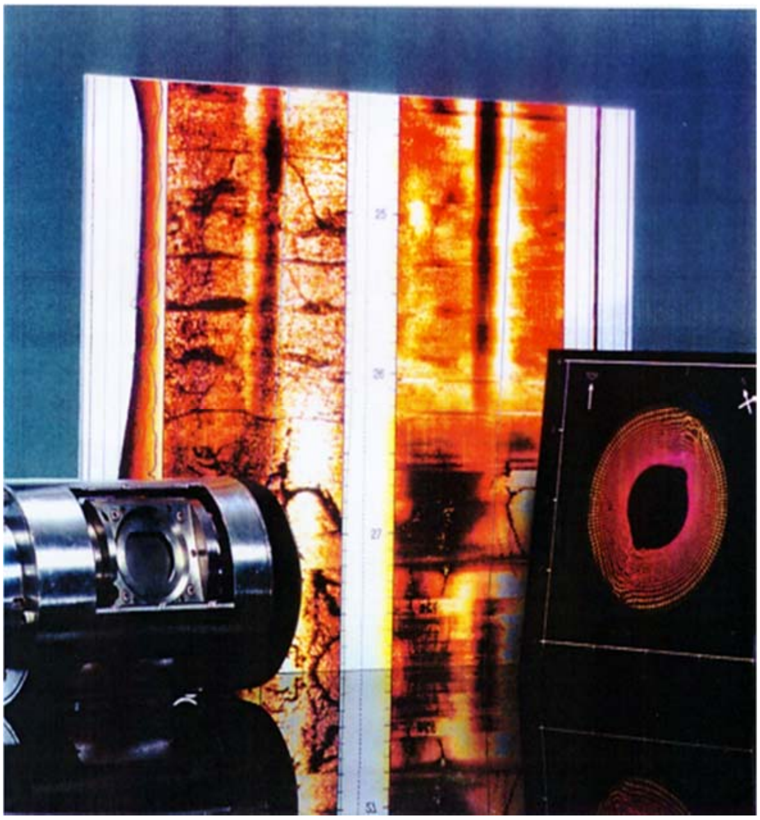
Rxo = Resistivity of flushed zone

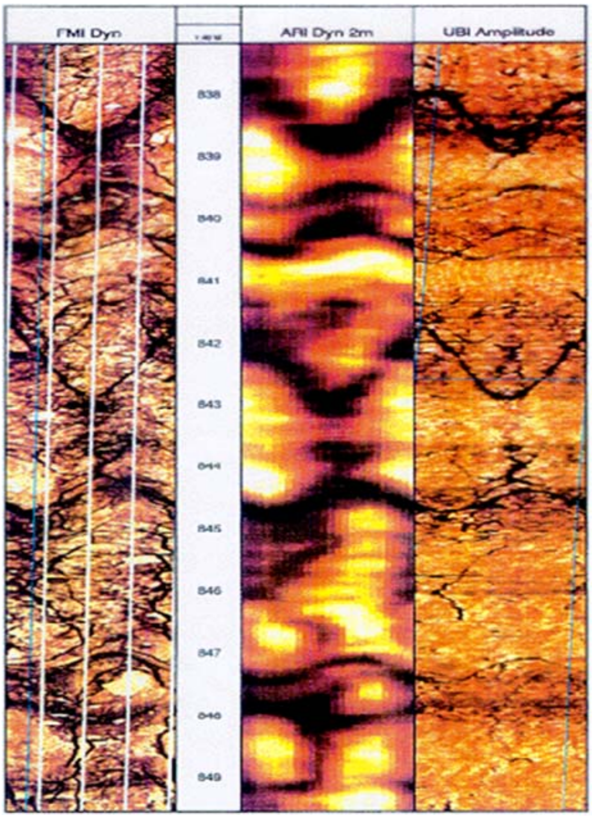
Rt = True resistivity of uninvaded zone

Sw = Water saturation

Sxo = Mud filtrate saturation in flushed zone

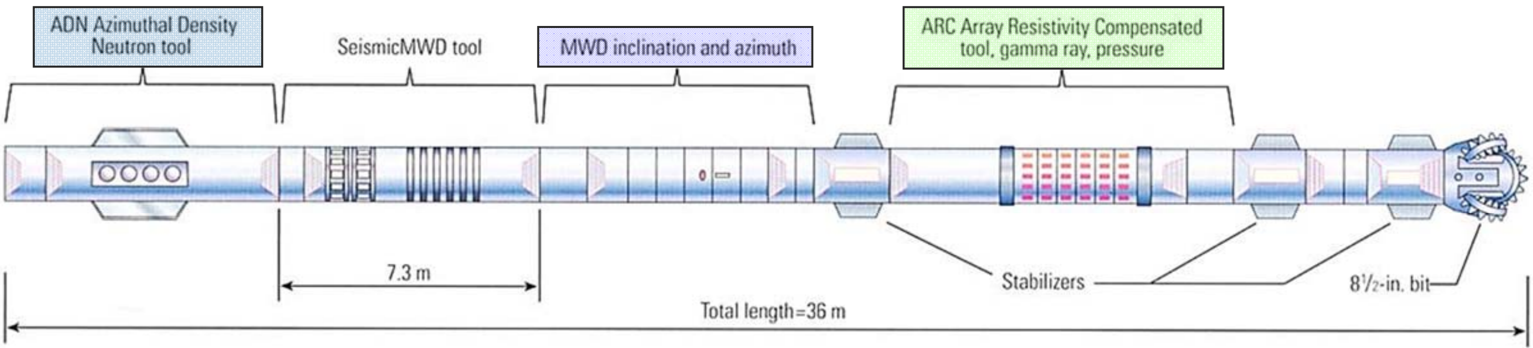
Borehole imaging (BHI)





Ultrasonic image: direct, visual layer information (lithology, boundaries and fractures)

Logging while drilling (LWD)



Bottomhole assembly. Other LWD tools, including the ADN Azimuthal Density Neutron tool and the ARC Array Resistivity Compensated tool, accompanied the SeismicMWD tool.

From Schlumberger Oilfield Review

Exploration tools & techniques

Operations geology

- Drilling (Reminder)
- Completion (Reminder)
- Logging
  - Mud logging
  - Wireline logging
  - "Quick look" analysis
  - Formation sampling
  - Dynamic measurements

Archie's law - Formation factor (F)

Archie's formula

- **In the water zone: Sw = 1**

$$Rt = \frac{a}{\Phi^m} \cdot Rw \quad \Rightarrow \quad Rw = Rt \cdot \frac{\Phi^m}{a}$$

$$F = \frac{a}{\phi^m}$$

The proportionality factor **F** is called **Formation Resistivity Factor**. It is the ratio of resistivity (Ro) of a sample with 100% water to water resistivity (Rw). It depends on lithology and on rock porosity (determined in lab)

The resistivity Ro is proportional to the water resistivity Rw

$$Ro = F \cdot Rw \quad \Rightarrow \quad F = R_o / R_w$$

- **In the hydrocarbon zone**

$$Rt = \frac{a}{\Phi^m} \cdot \frac{Rw}{Sw^n} \quad \Rightarrow \quad S_w = \sqrt[n]{\frac{a}{\phi^m} \frac{R_w}{R_t}}$$

a , m , n are constants values:
m and **n are determined in petrophysical laboratory**
Usually **a = 1 , m = 2, n= 2**

- **Sandstones: a = 0.81 ; m = n = 2**
- **Carbonates: a = 1 ; m = n = 2**
  (m varies: 1.3 < m < 2.5)

Archie's formula

In the hydrocarbon zone

- **Archie formula in uninvaded (non-flushed or «virgin») zone**

$$Rt = \frac{a}{\Phi^m} \cdot \frac{Rw}{Sw^n} \Longrightarrow S_w = \sqrt[n]{\frac{a}{\phi^m}\frac{R_w}{R_t}} \Longrightarrow S_{hc} = 1 - S_w$$

Hydrocarbon Saturation

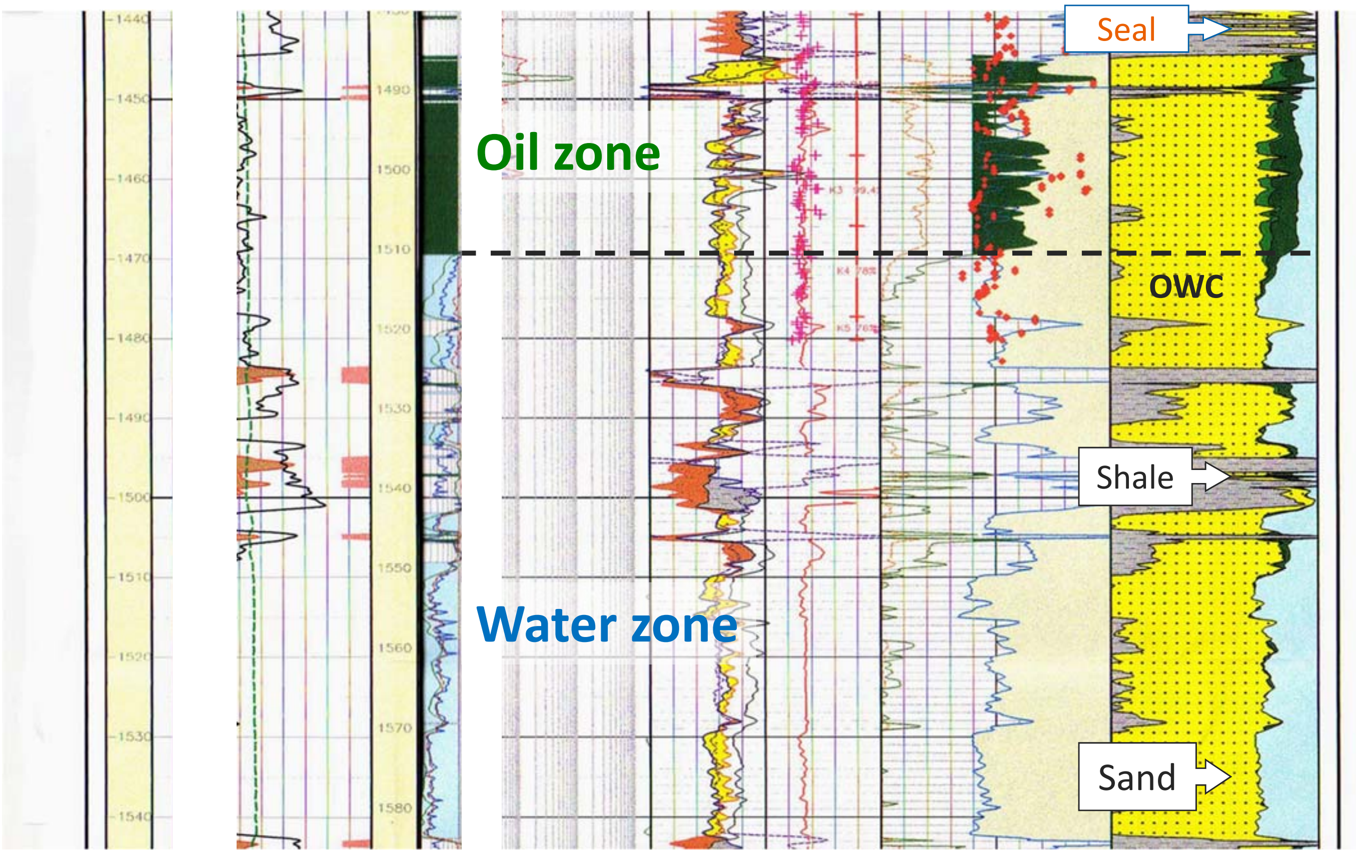
- **Archie formula in flushed zone:**

$$Rxo = \frac{a}{\Phi^m} \cdot \frac{Rmf}{Sxo^n} \Longrightarrow S_{xo} = \sqrt[n]{\frac{a}{\phi^m}\frac{R_{mf}}{R_{xo}}} \Longrightarrow S_{hr} = 1 - S_{xo}$$

Residual HC Saturation

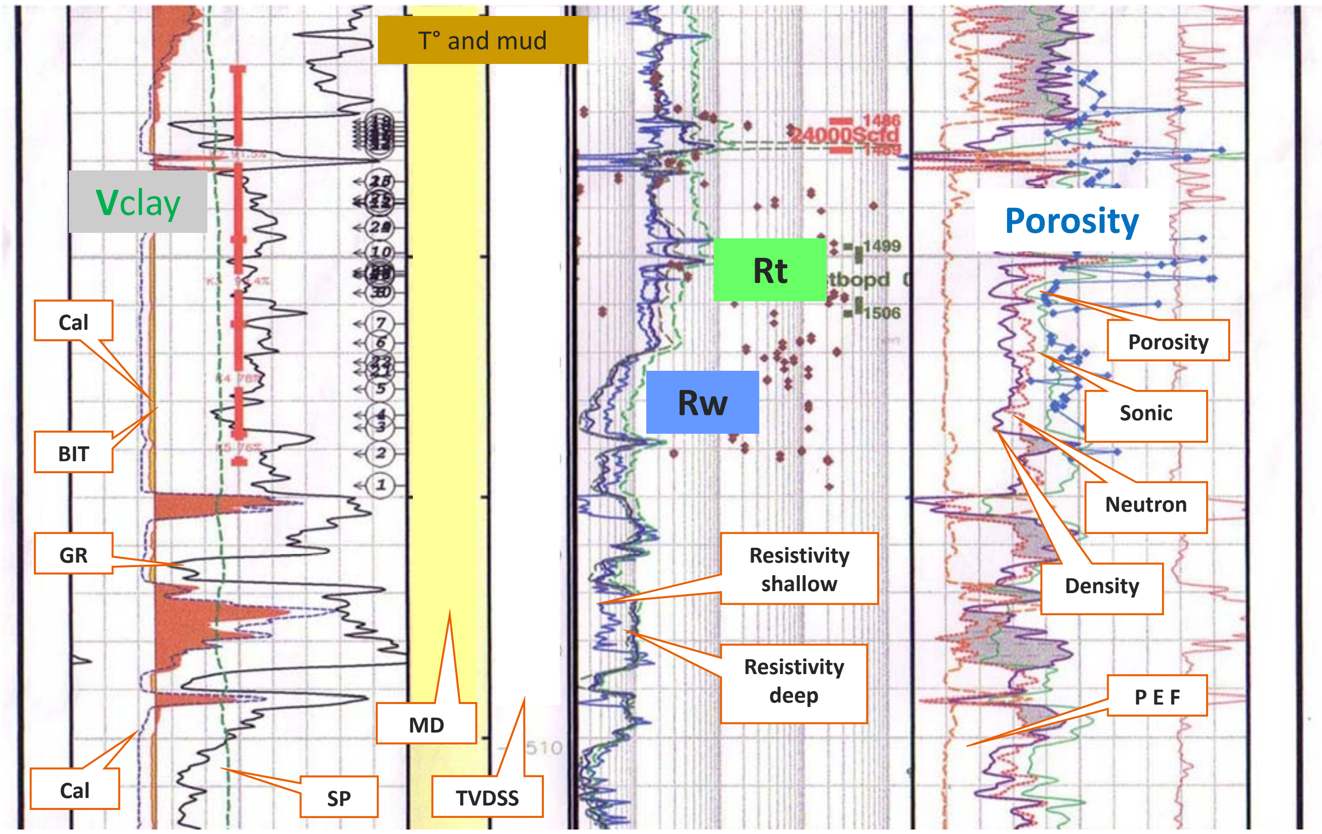
- **Rt and Rxo values are read on logs**
  - **R**t from Laterolog deep or Induction deep
  - **R**xo from Microresistivity log
  - **R**mf = Mud filtrate resistivity

Well-log automated interpretation software



OWC = Oil Water Contact

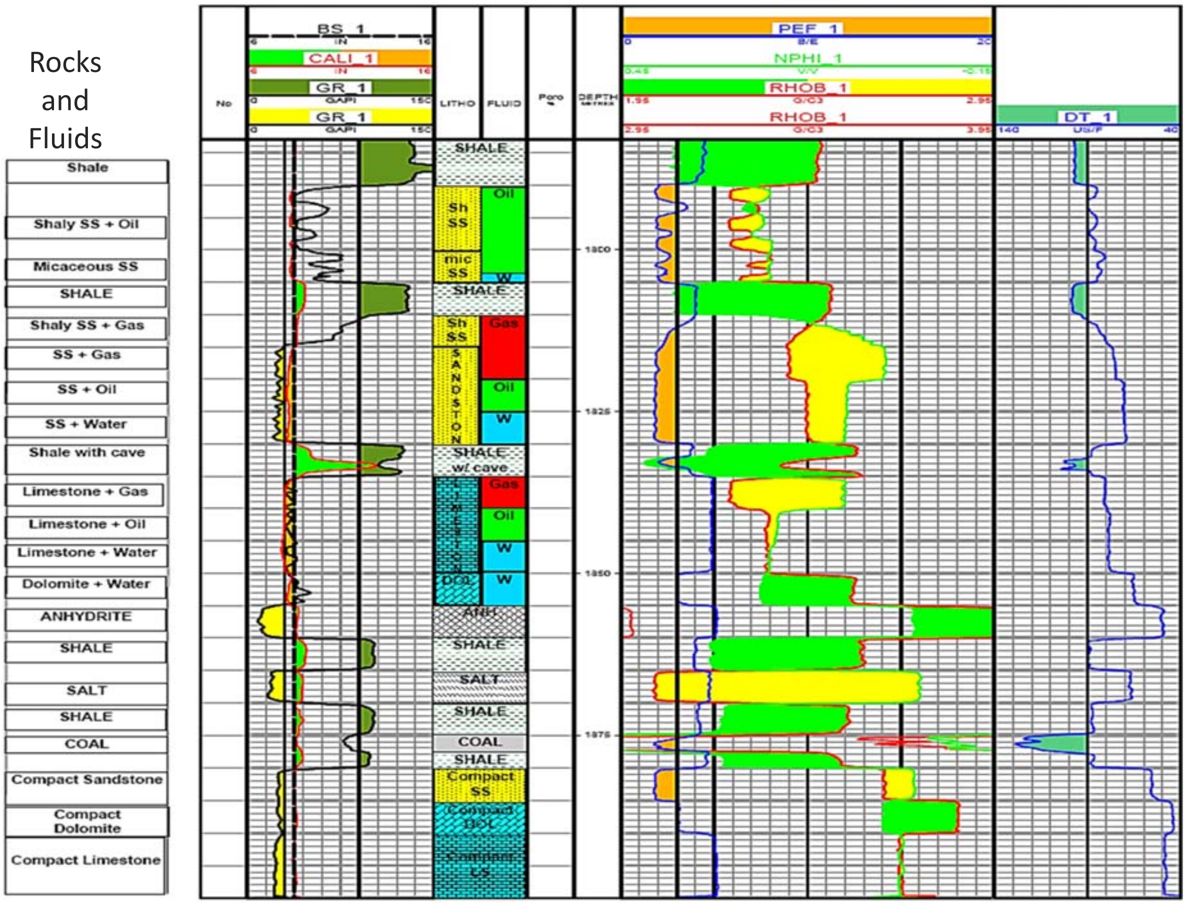
Calculation of saturation



Summary - Main tools and specific applications

	Measured parameter	Depth of investigation	Vertical resolution	Application
Caliper	Borehole diameter	none	1 to 3 cm	• Cave and mud-cake / reservoir identification
GR	Natural radioactivity of formation	30 cm	30 cm	• Shale / sand identification
Resistivity	Formation resistivity & conductivity (both rocks & fluids)	3cm to 2 m	A few cm to 1m	• Fluid identification • Fluid saturation
Neutron **Density** **Sonic**	• Fast neutrons emission feedback measurement • Stimulated gamma ray measurement • Acoustic wave transit time measurement	12 to 25 cm ~10 cm 1 to 12 cm	40 - 60cm 10 cm 60 cm	• Formation lithology • Reservoir porosity

Examples of typical quick-look analysis results



Well data analysis & interpretation – Key points

- **Borehole logging provides detailed data collection around wellbore**
  - Combination of proximal and distal data (e.g. shallow & deep)
  - Identification of lithological succession in the well
- **Interpretation of well-log recordings**
  - Identification of reservoir formations
  - Estimation of fluid nature and content (water, oil, gas)
  - Calculation of rock porosity and fluid saturation
  - Comparison with lab's data (petrophysical core analysis)
- **Correlation between wells**
  - Correlation of key surfaces through the basin
  - Calibration of seismic data (well tying for depth conversion)

End Day#4

Notes

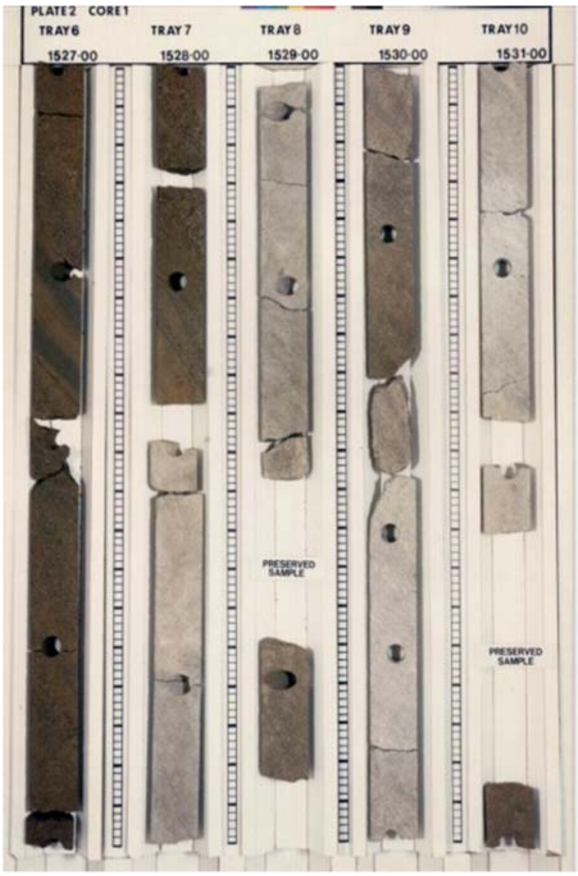
Notes

Exploration tools & techniques

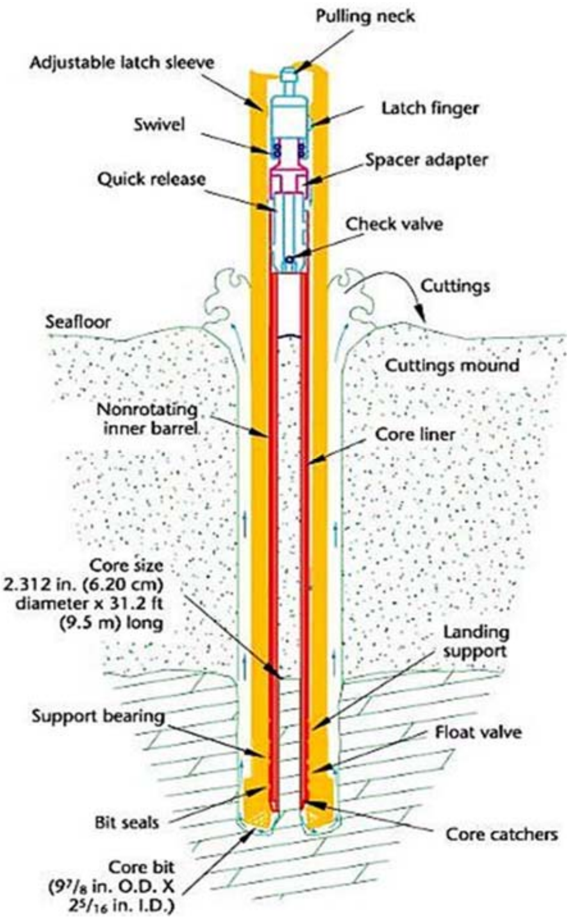
- **Operations geology**
  - Drilling (Reminder)
  - Completion (Reminder)
  - Logging
    - Mud logging
    - Wireline logging
    - "Quick look" analysis
    - Formation sampling
    - Dynamic measurements

Core sampling

Core bit



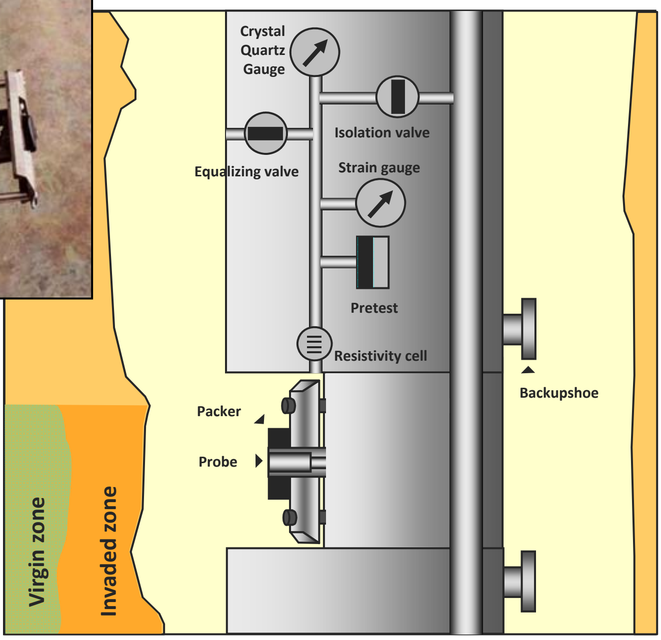
Core recovery



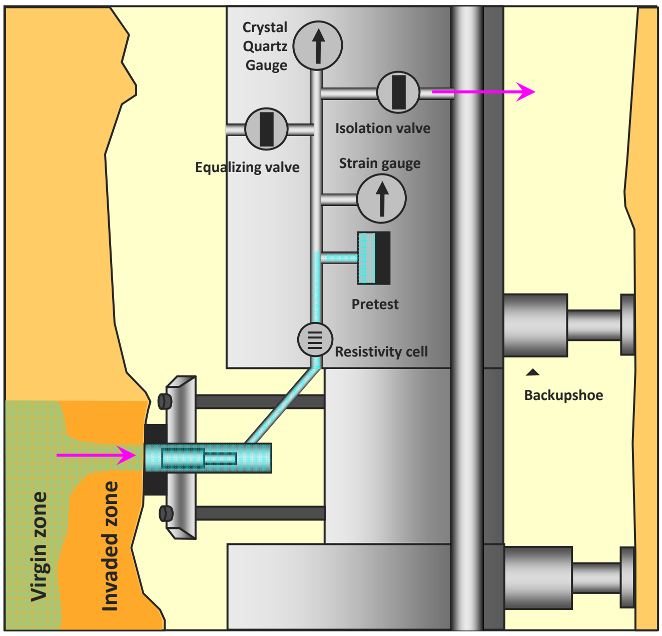
Fluid sampling

Modular Dynamic Formation Tester (***R**epeat **F**ormation **T**ester)*

MDT / RFT logging tool



MDT: closed tool



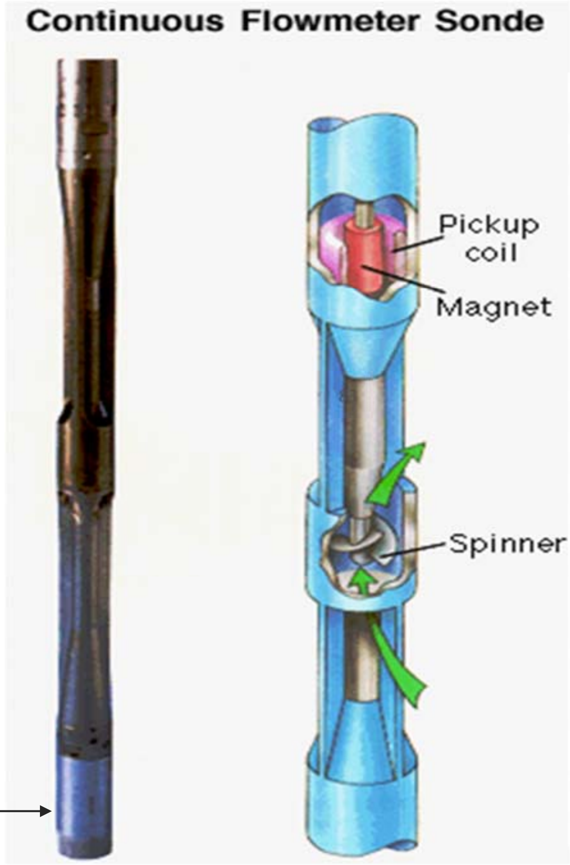
MDT: open tool

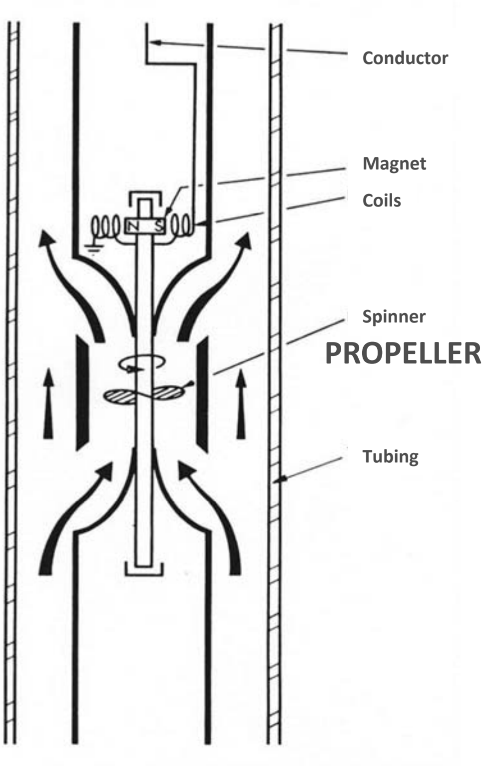
Exploration tools & techniques

- **Operations geology**
  - Drilling (Reminder)
  - Completion (Reminder)
  - Logging
    - Mud logging
    - Wireline logging
    - “Quick look” analysis
    - Formation sampling
    - Dynamic measurements

Well test: production potential evaluation

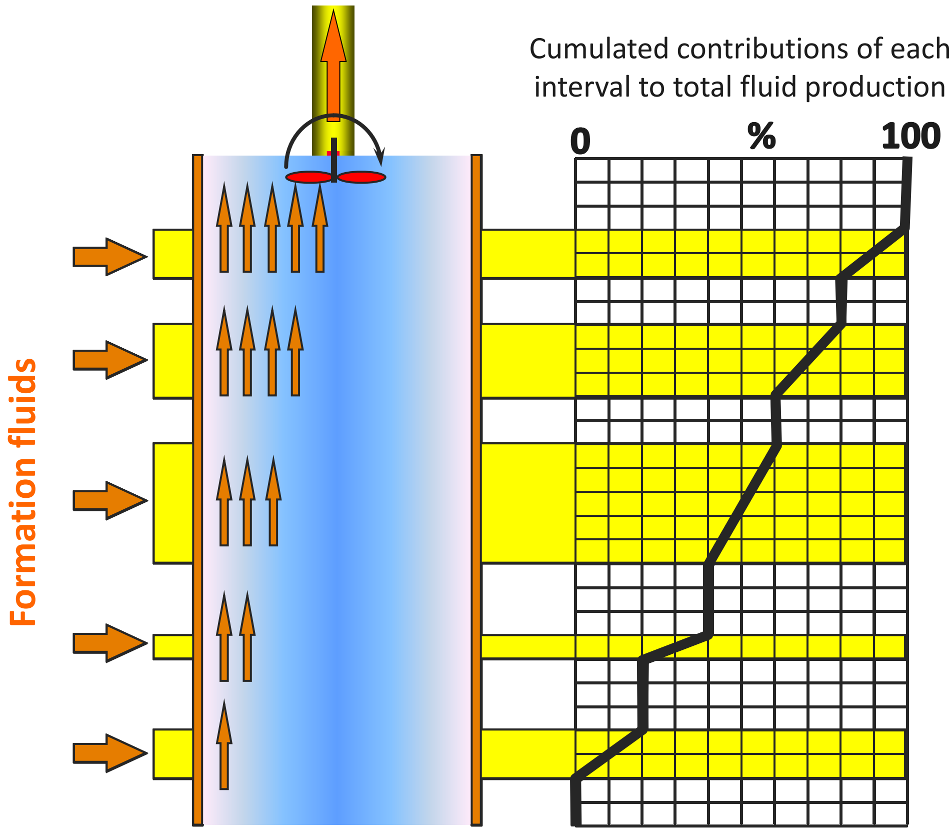
Production Logging Tool (PLT)

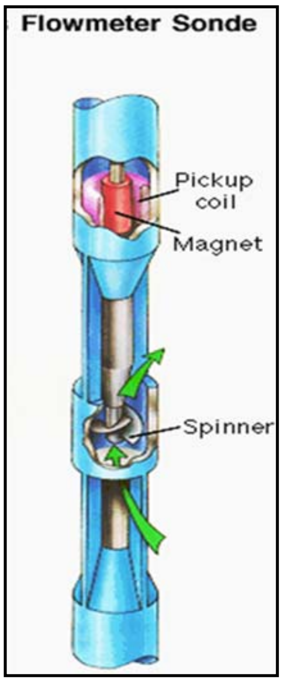




From Schlumberger

PLT: continuous flowmeter





Information from propeller speed measurement is converted into production

(speed is proportional to flow)

Basin infilling and organization

Basin infilling and organization

V

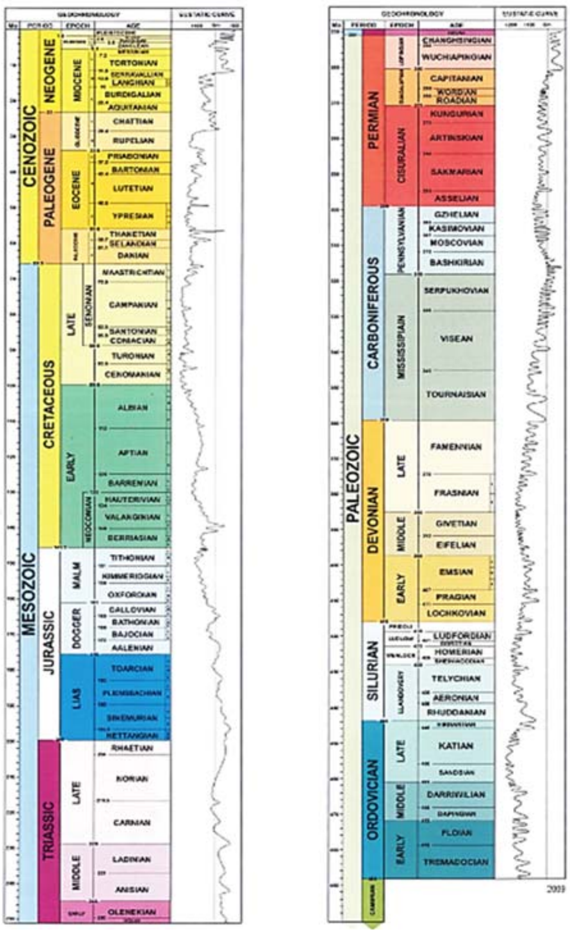
- Principles of stratigraphy
- Introduction to sequence stratigraphy

Definitions & concepts

Definitions

- Stratigraphy: branch of geology that studies the arrangement & succession of rock strata, layers & layering - especially the distribution, deposition, and age of sedimentary rocks – and the relative chronology of their deposition & related geological events
  - Law of superposition
  - Principle of paleontological identity and faunal succession
  - Law of facies (Walther)
- Facies: body of sedimentary rock with specified characteristics. Distinctive rock unit that was formed under certain geological conditions, reflecting a particular depositional process or environment. (Nature of the sediment: no indication on age)
- Isochron: time boundary (or time slice/interval) with same age everywhere (independent from facies)

Geologic time scale - Stratigraphic column

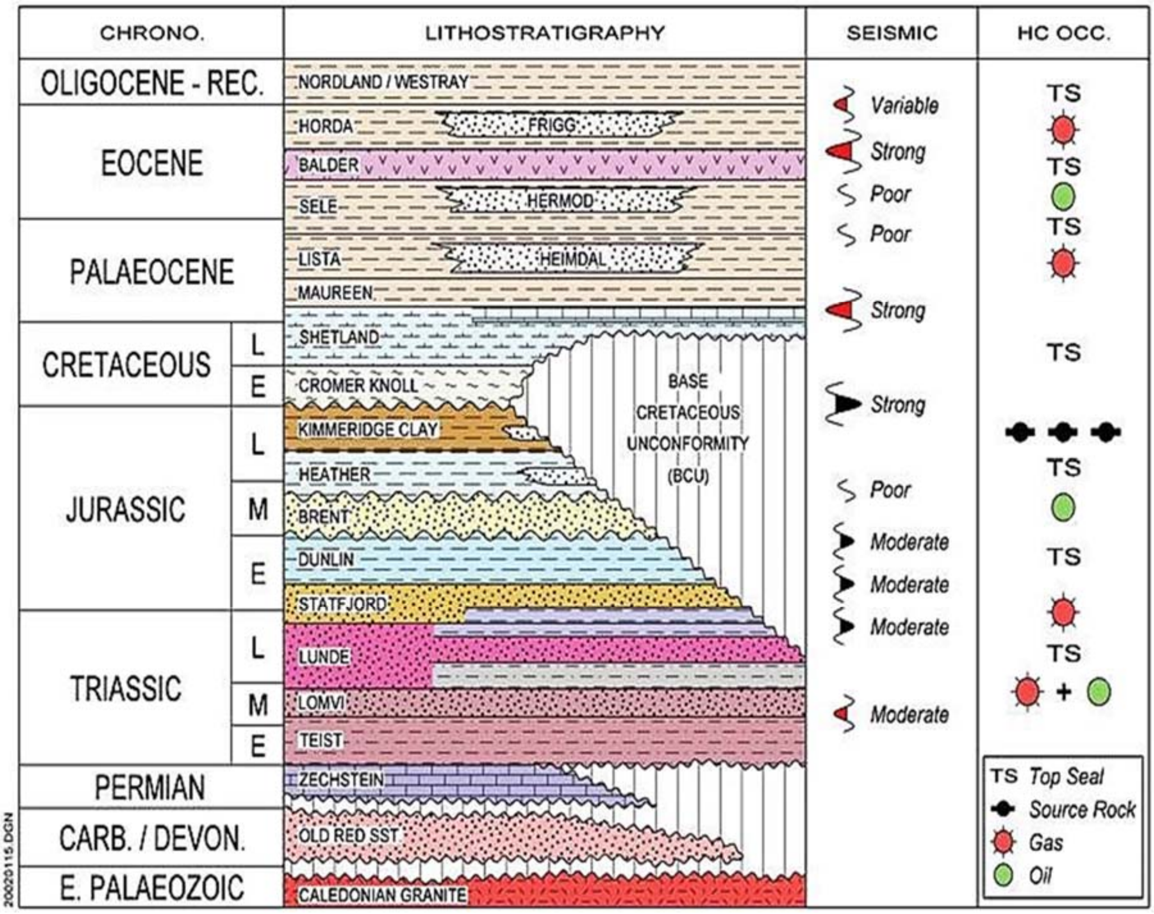


Courtesy of TOTAL

Reference chronostratigraphy chart
(stages, periods and eras)
of an oil company

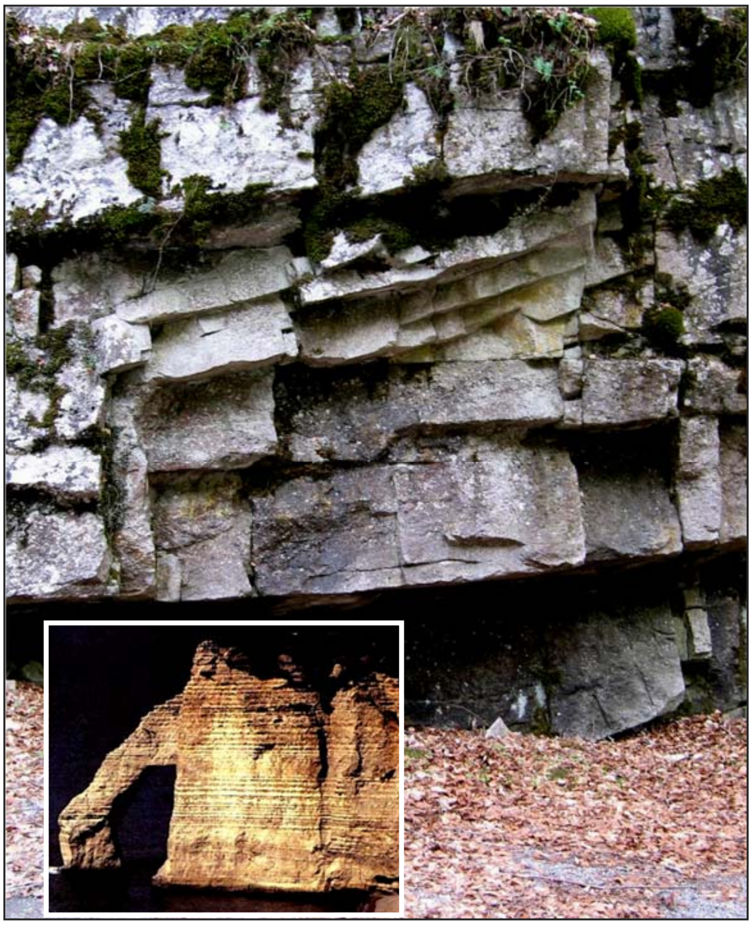
Stratotype: *reference rock outcrop where a specific geologic stage or period was defined (e.g. Lutician defined in Paris)*

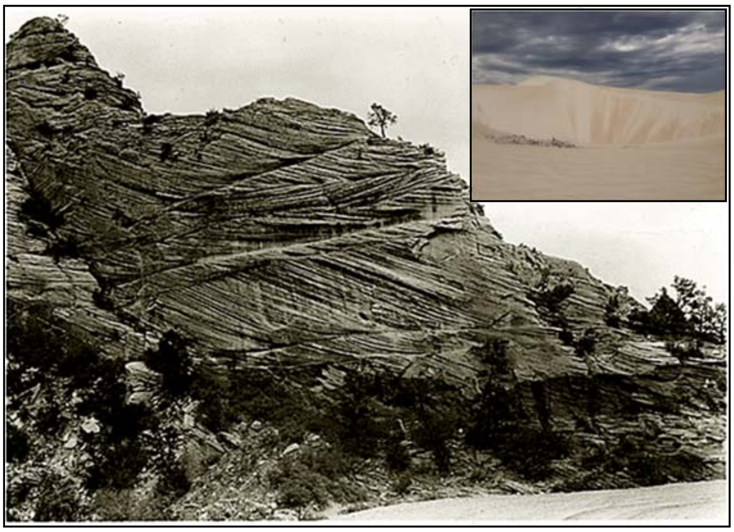
Regional stratigraphy - Hydrocarbons occurrences



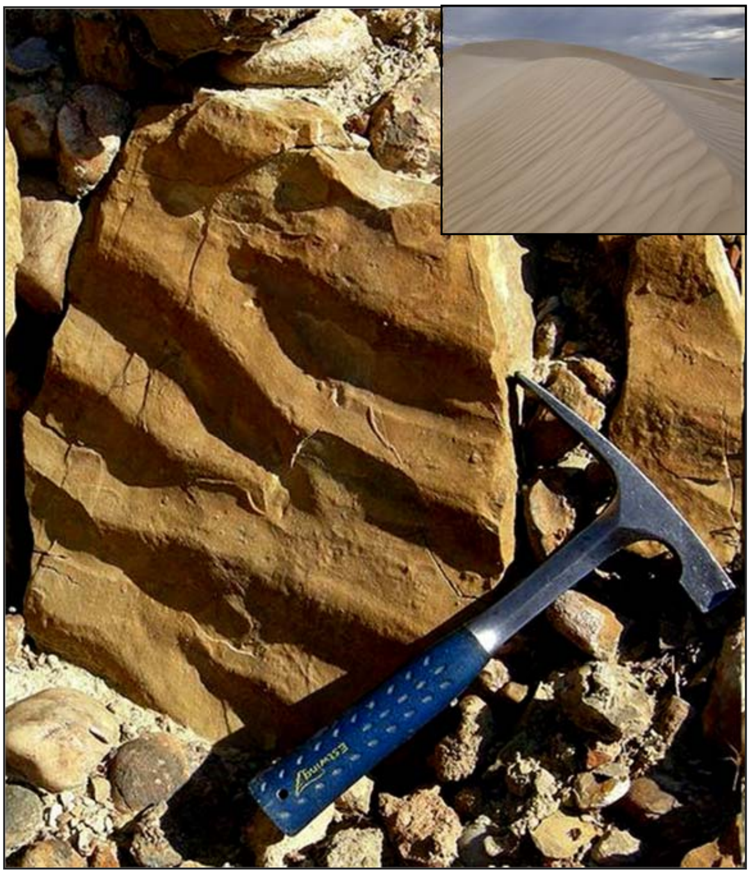
Regional lithostratigraphy
(oil field in Norway)

Stratification





Sedimentary structures



Ripple marks (symmetrical)

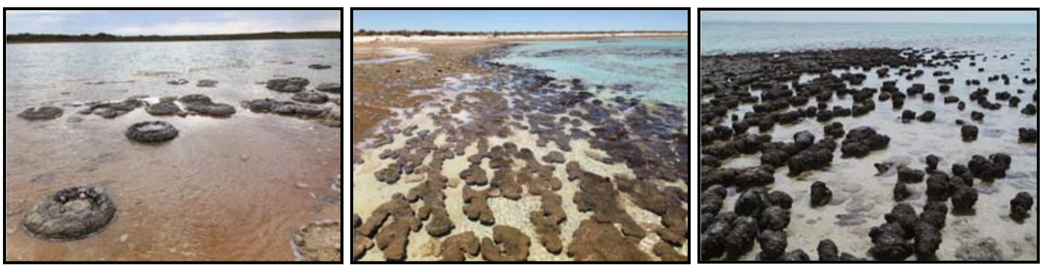
Flute casts (current scours)

Sedimentary features

Bioturbations
(worms tracks)

Stromatolites
"Blue algae"/Cyanobacteria)

Present-day stromatolites



Stratigraphy - key points

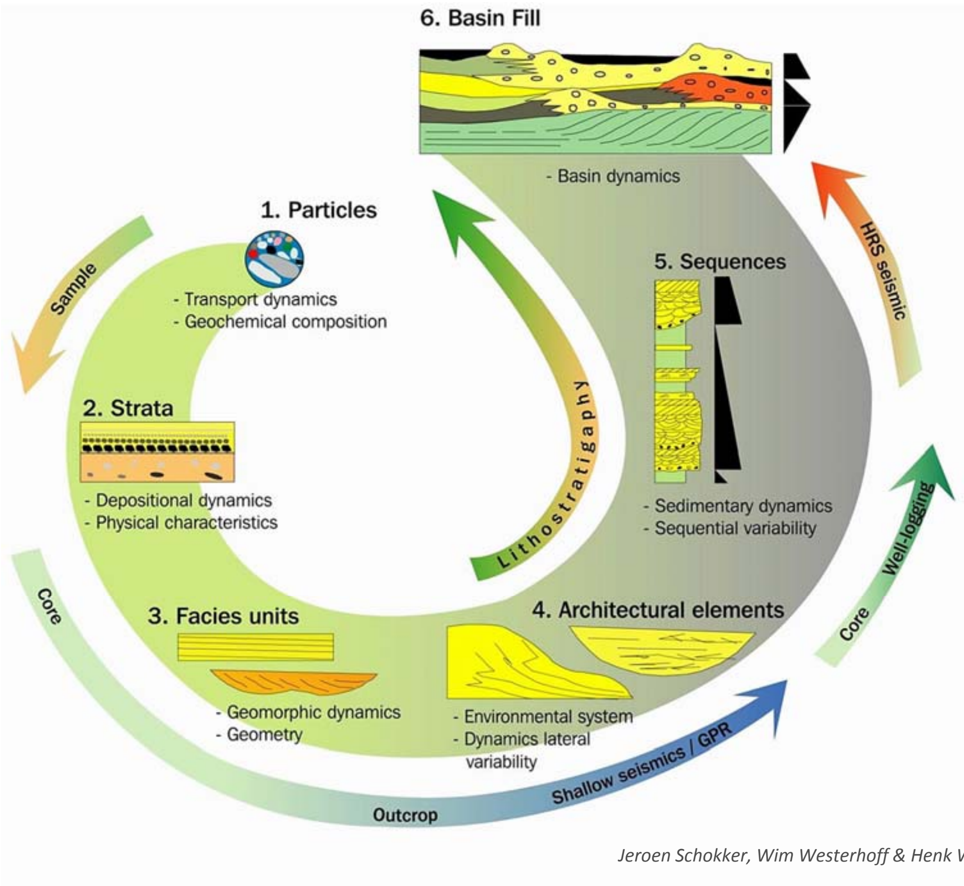
- **Lithostratigraphy:** deals with physical lithologic (rock type) changes, both vertically in layering or bedding of varying rock type and laterally reflecting changing environments of deposition (facies change).
- **Chronostratigraphy:** studies the relative (not absolute) age of rock strata, by deriving geochronological data for rock units to understand the geologic history of all rocks - and eventually arrange their sequence of deposition - within a region.
- **Biostratigraphy:** based on fossil evidence in the rock layers. Strata from widespread locations containing the same fossil fauna and flora are correlatable in time. The geologic time scale was developed (1800's) based on the evidence of biostratigraphy and faunal succession.
- **Stratigraphy** is commonly used to delineate the nature and extent of **hydrocarbon-bearing reservoir rocks**, seals and traps.

Notes

Basin infilling and organization

- Principles of stratigraphy
- Introduction to sequence stratigraphy

Sedimentary fill hierarchy



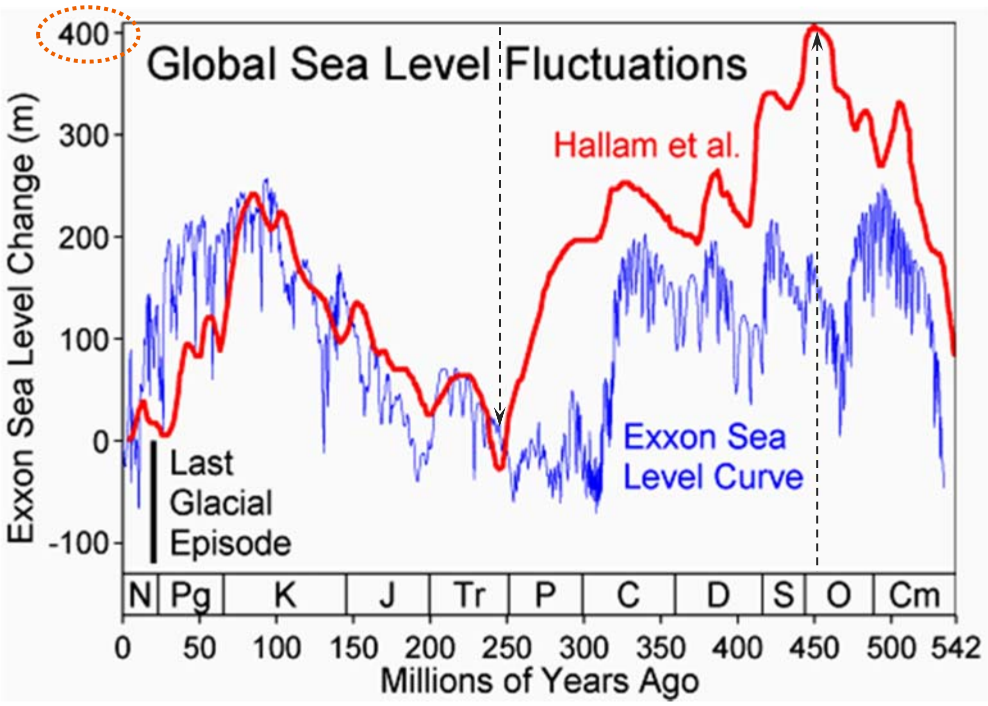
Jeroen Schokker, Wim Westerhoff & Henk Weerts after Heinz & Aigner, 2003

Concepts

▶ Relative sea level variations

- The configuration of the continents and seafloor have changed due to plate tectonics during Earth's history. This affects global sea level by determining the depths of the ocean basins.
- The depth of the ocean basins is related to the age of the oceanic lithosphere: as lithosphere becomes older, it gets colder, denser and sinks.
- (Several small oceanic plates (hotter hence lighter) produce shallower oceans and higher sea levels, while fewer plates (colder hence denser) result in deeper oceans and lower sea levels)
- Long-term changes in sea level are the result of changes in the oceanic crust, with a downward trend expected to continue in the very long term.

Frequency of sea level variations



Sea level variations during the Phanerozoic

Definitions

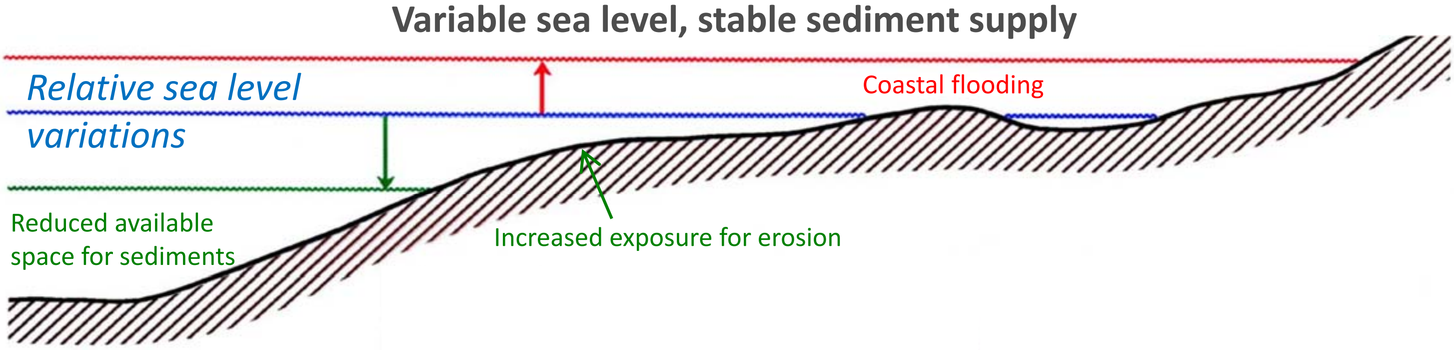
- **Eustacy**

  Global sea level change reflecting a change in the volume of water, or in the shape / capacity of the oceanic basins
  - **Transgression**: when land is lost to the sea *(continent flooding)*
  - **Regression**: when land is gained from the sea floor
- **Isostacy**
  - **Subsidence**: downward motion of the Earth's surface *(relative to sea level's reference)*
  - **Uplift**: opposite of subsidence *(elevation increase)*
- **Eustacy vs isostacy**
  - Eustatic effects are caused by global sea level change
  - Isostatic effects are caused by local changes in land elevation
    (tectonic, thermal [swelling/cooling], sedimentary [loading], glacial [rebound],…)

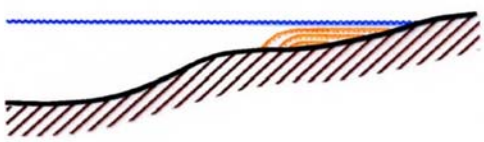
➢ **Relative sea level variations have either isostatic or eustatic causes, or a combination of both**

Sedimentation vs sea level variations

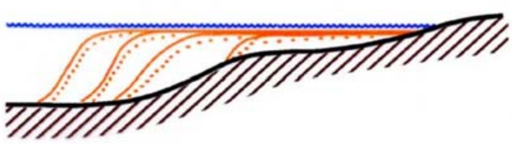
Variable sea level, stable sediment supply



Stable sea level, variable sedimentation rate

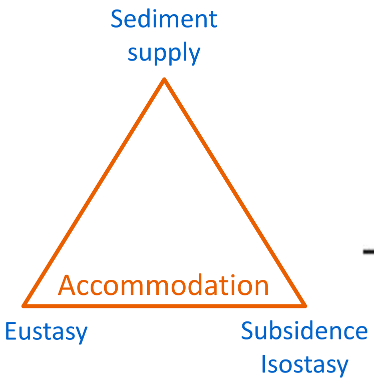


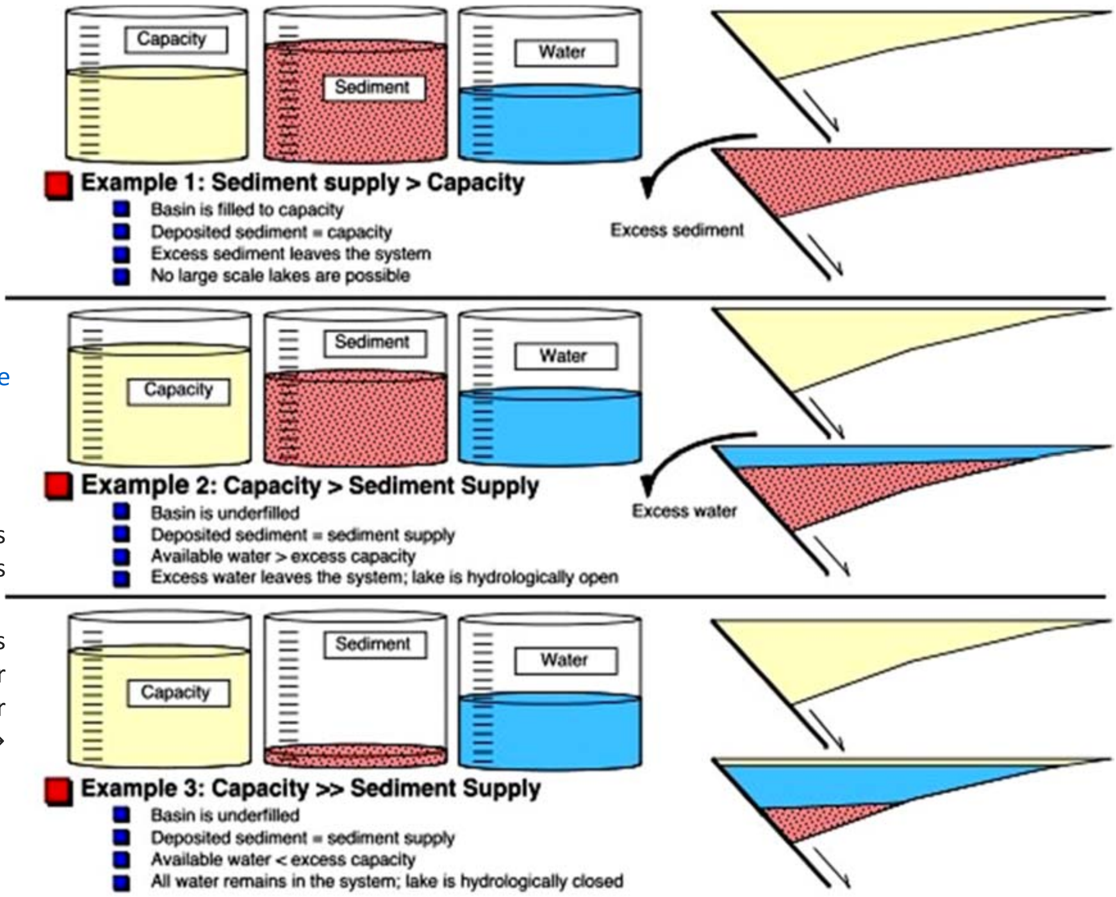
Weak clastic supply



Strong clastic supply

Sedimentation vs sea level variations



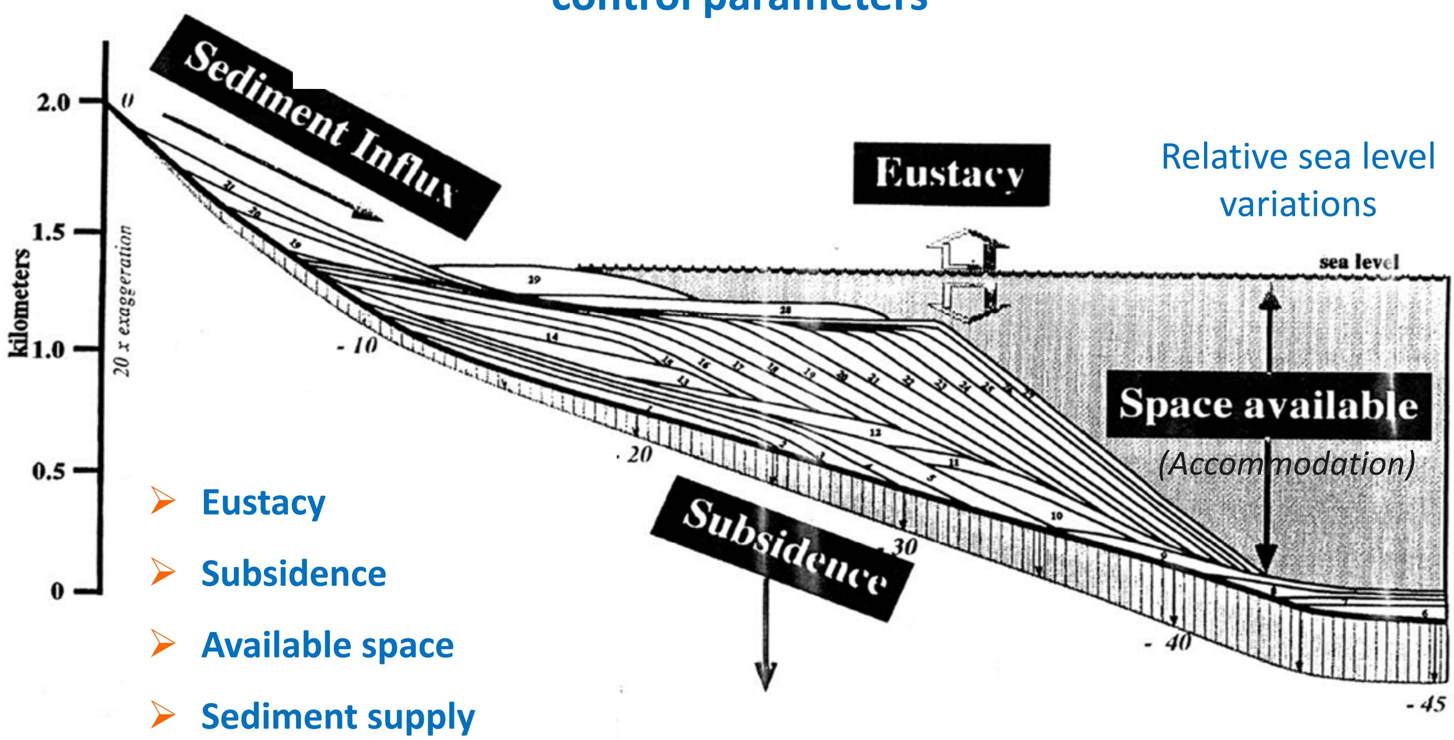


Three main variables:

- **Relative sea** level variations (eustacy [global ocean level] vs isostacy [tectonic activity])
- **Sediment supply** (exposed reliefs [sediment source availability for erosion] + climate [water availability for transport] → sedimentation rate)
- **Basin capacity** (accommodation)

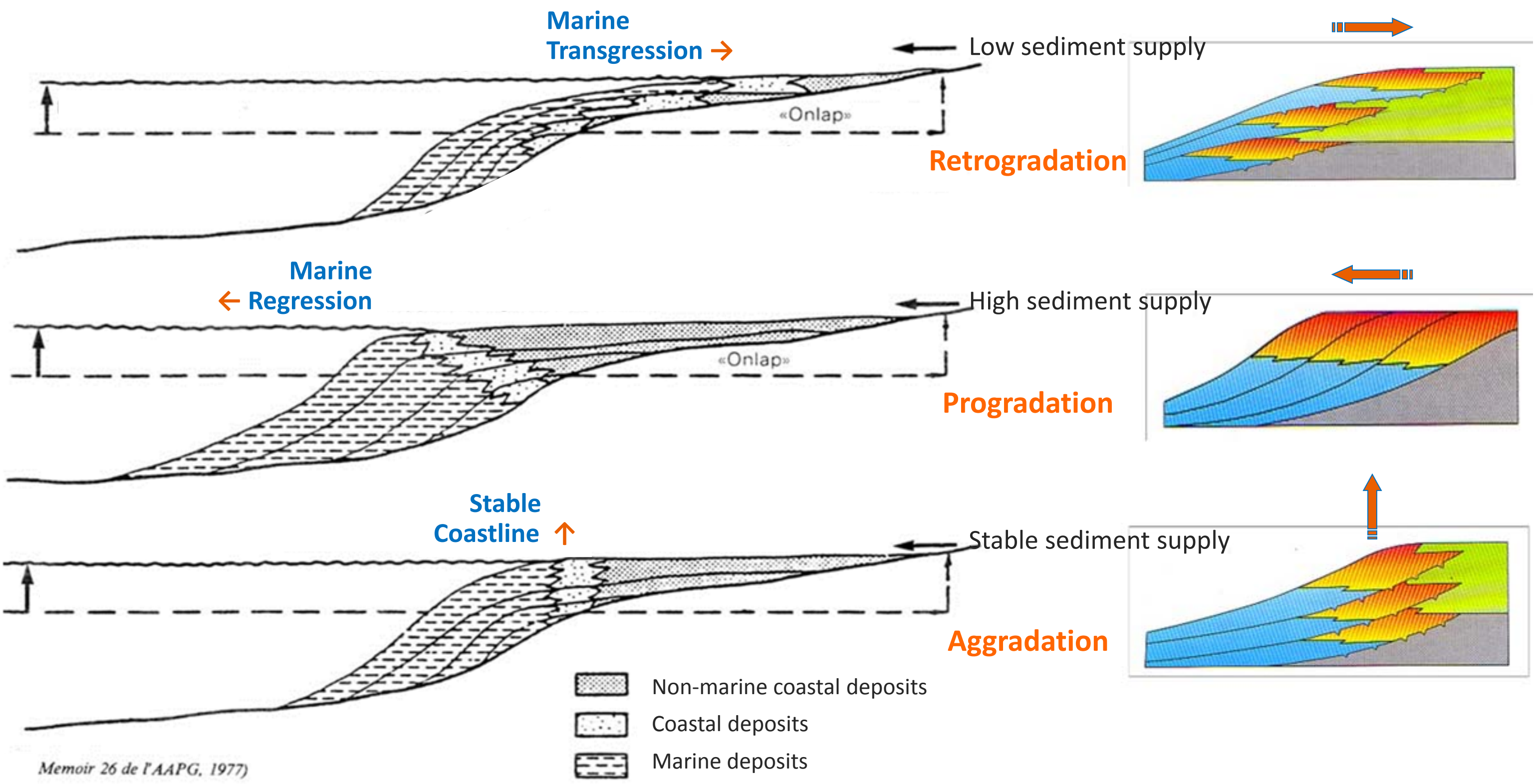
Parameters controlling sedimentation

Depositional model
control parameters



- Eustacy
- Subsidence
- Available space
- Sediment supply

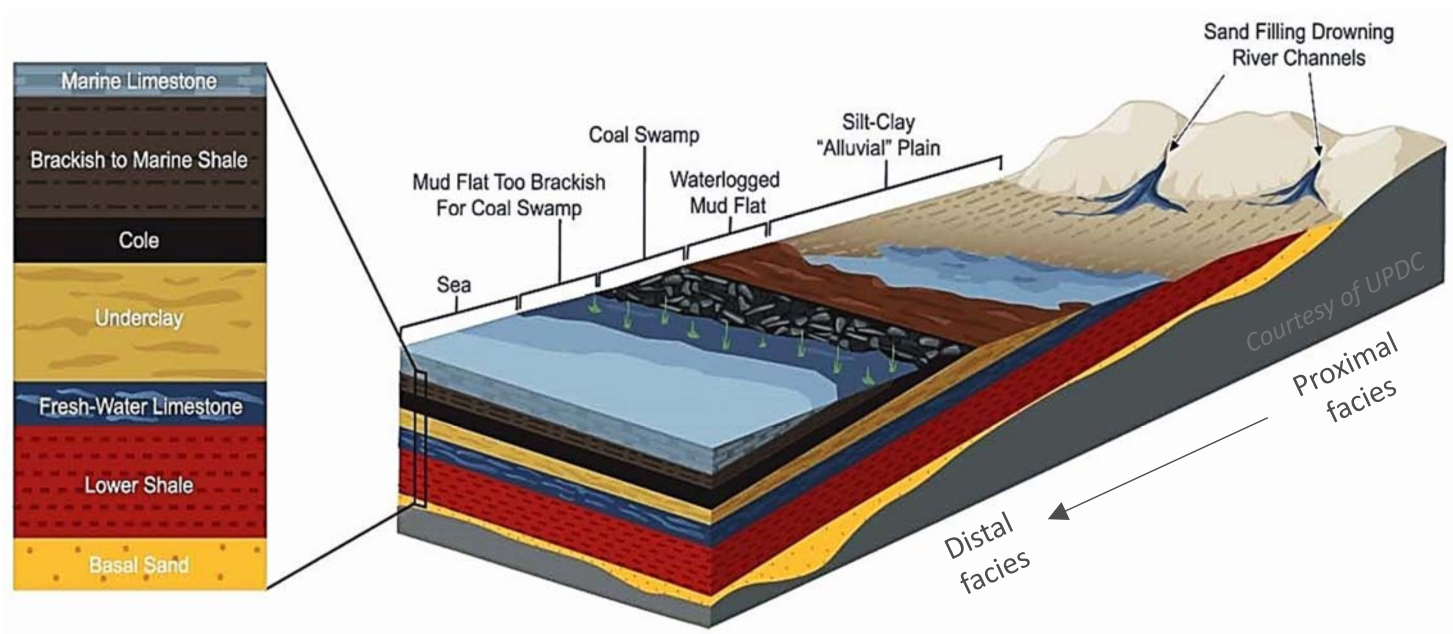
Sea level variations vs sediment supply



Consequences of sediment supply variations during relative sea level rise

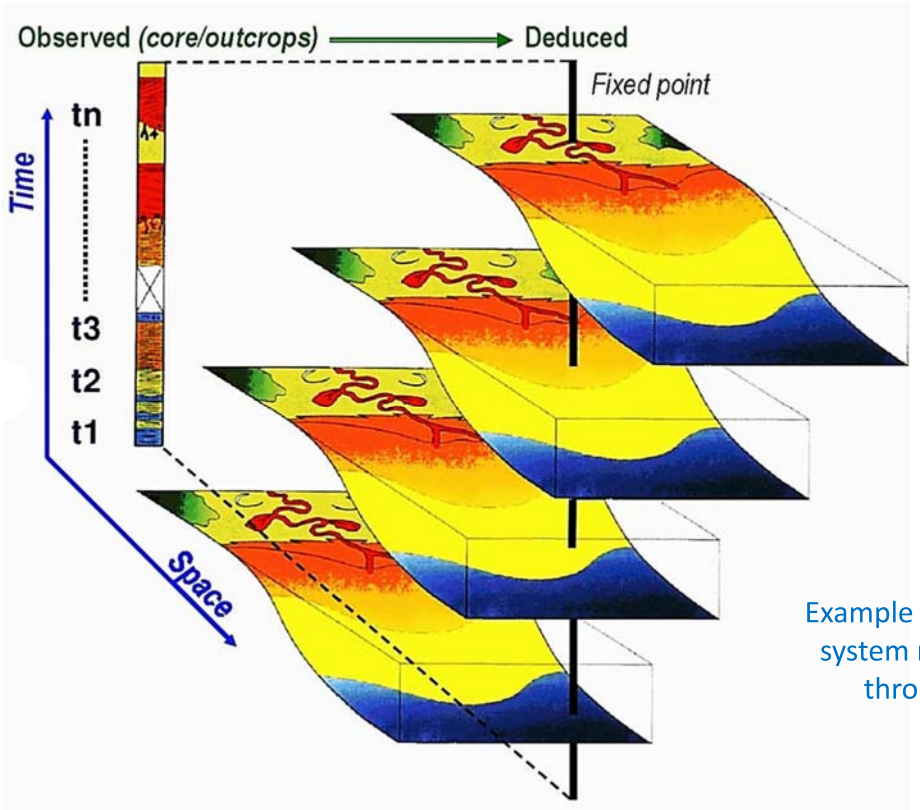
Walther's law (1894)

« Facies adjacent to one another in a continuous vertical sequence also accumulate adjacent to one another laterally »



Allows to use modern depositional processes (analogues) to understand past processes.

Walther's law: sediments piling organization

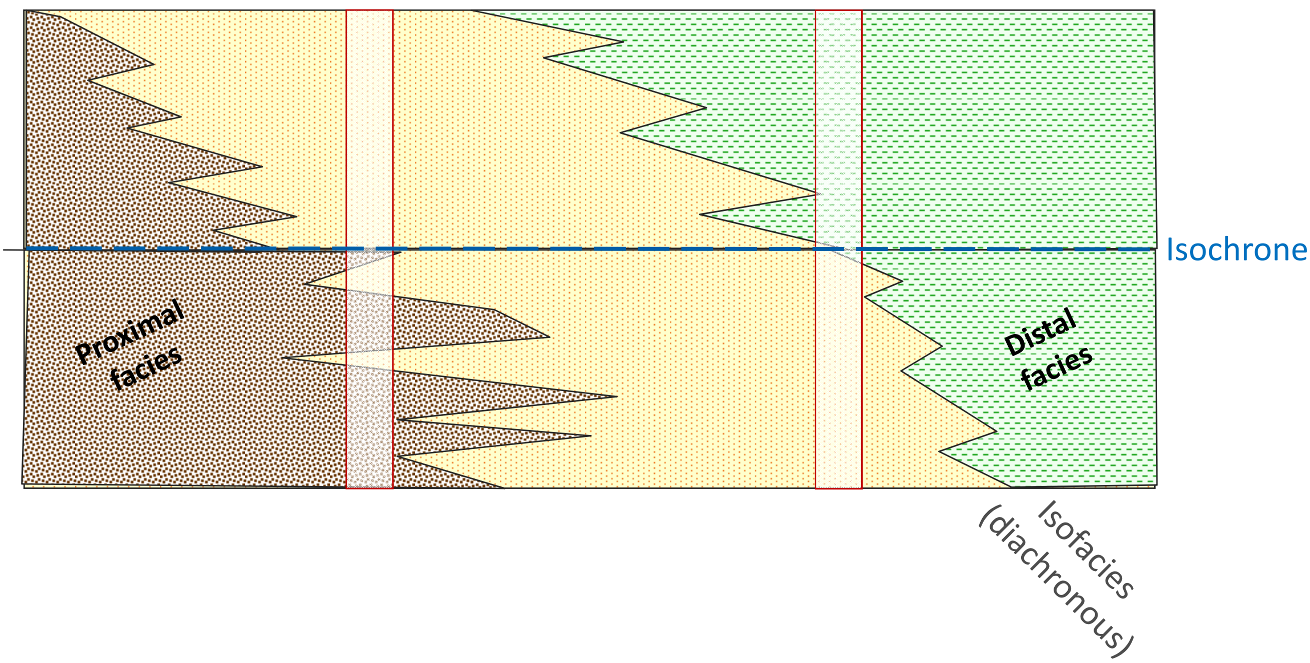


Example of a depositional system moving forward throughout time

"Facies adjacent to one another in a continuous vertical sequence also accumulated adjacent to one another laterally" (Walther, 1894)

Litho- vs chrono-stratigraphy

Facies and relative chronology

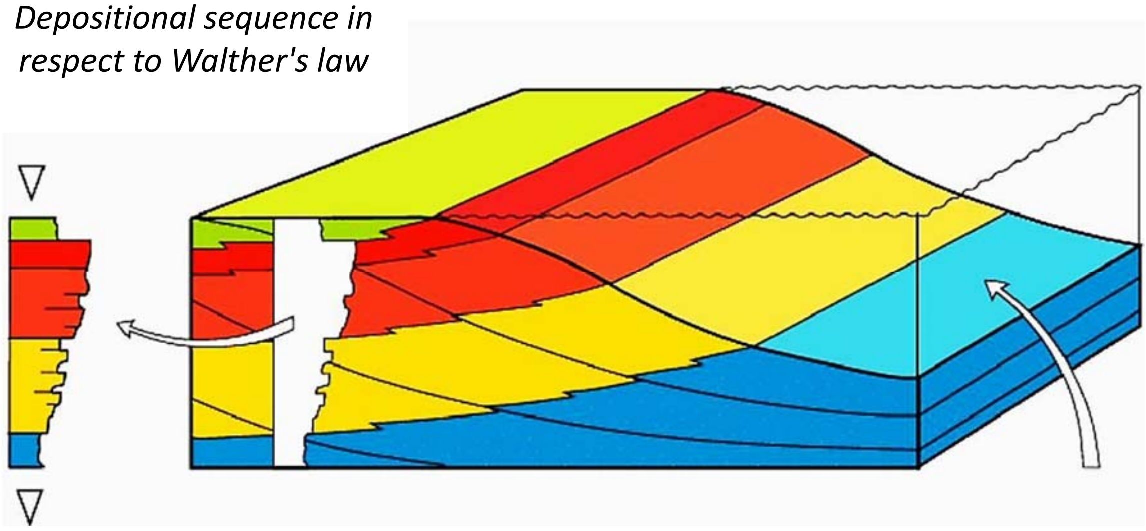


Vertical succession of sediments

Sedimentary sequence

vertical stacking of facies that has recorded their lateral succession throughout geologic times

Depositional sequence in respect to Walther's law



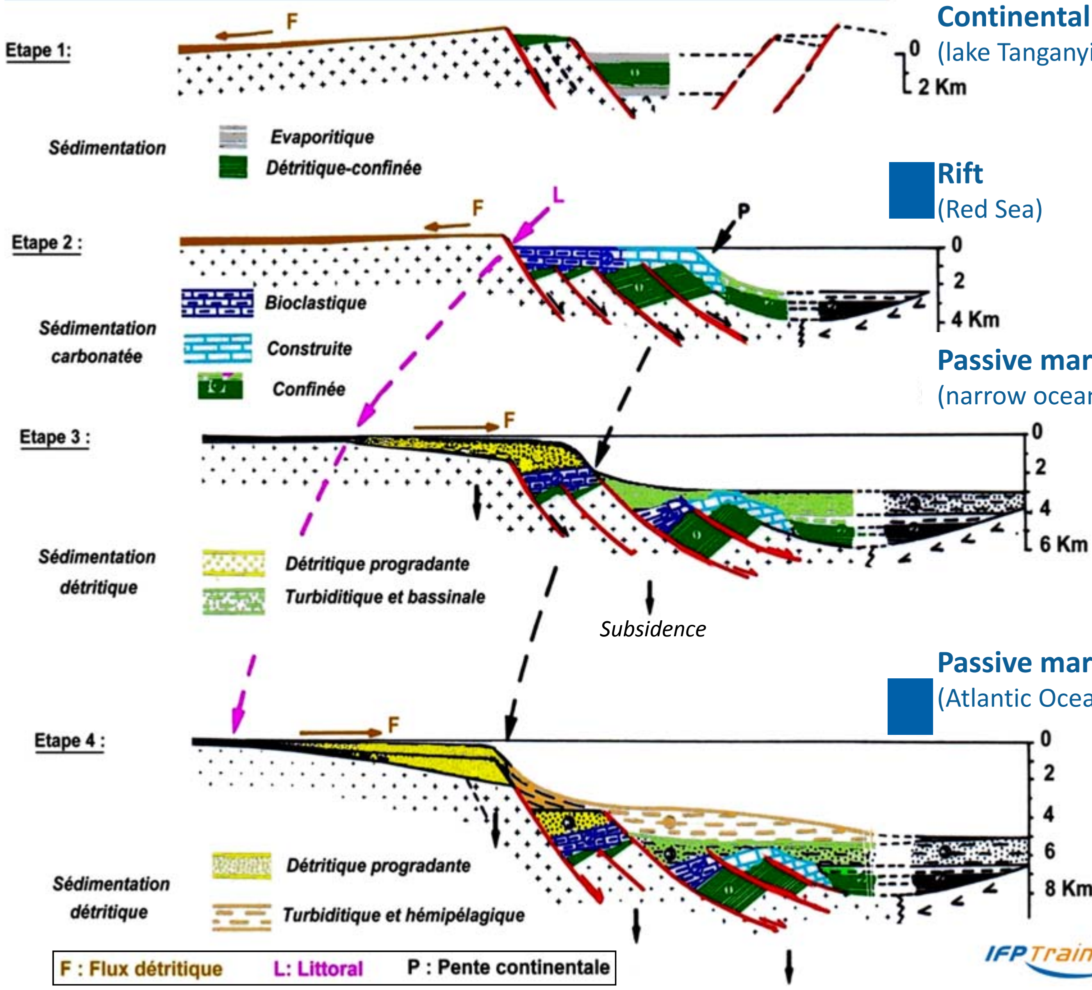
coarsening up sequence

Example of a depositional system that has moved forward throughout time: Depositional system progradation (proximal facies overlapping distal facies)

Earth geodynamics vs Depositional environments

Evolution of sedimentation during a rifting process

Tectonic phases from a rift to a passive margin and related environments and facies



Continental rift (lake Tanganyika)

Rift (Red Sea)

Passive margin (narrow ocean)

Passive margin (Atlantic Ocean)

Introduction to sequence stratigraphy - Summary

- **Sequence stratigraphy** is based on the systematic subdivision of the sediment pile by well-defined **surfaces**
- These surfaces are used to construct an **analysis framework** of the depositional settings in the sedimentary record
- The resulting interpretation is used to **predict sedimentary facies' extension** and characteristics
- **Sequence stratigraphy** is an integrated method that integrates all exploration tools (geology, geophysics, palynology, geochemistry,…) that aims at identifying:
  - The chronostratigraphic relationship between depositional layers
  - The basic units in each sedimentary pile, i.e. depositional sequences
- Characteristics of a depositional sequence
  - Bound by unconformities and correlative conformities
  - Composed of systems tracts
- A system tract is:
  - Bound by physical surfaces
  - Composed of elementary « units » (genetic units or parasequences)

Volumetrics

Volumetrics

VI

- Estimation of in-place hydrocarbon accumulations
- Conventional hydrocarbon recovery

Definition - Accumulation vs Reserves

- **Accumulation**: Volume of hydrocarbons in place to be estimated = Hydrocarbon deposit
- **Reserves**: Part of this volume that can be recovered by technical and economic procedures

"Reserves are defined as the estimated quantities of effluents (crude oil, natural gas, gas condensate, liquids recovered from natural gas) and associated substances, that are considered commercially viable to recover from a given accumulation, beginning at a future date, under specific economic conditions, using current technology, and subject to present-day legal restrictions".

Top 5 countries in 10^9 bbls

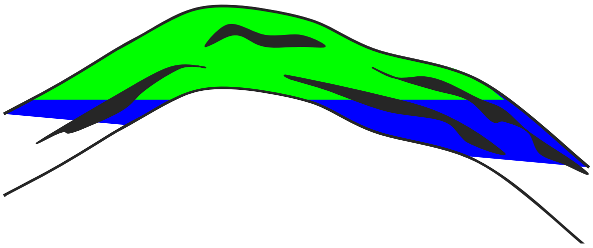
Venezuela: 296.5 , Saudi Arabia: 265.4 , Canada: 175.2 , Iran: 151.2 , Iraq: 143.1

Resources calculations basics

$$\text{Reserves} = \underbrace{GRV * N/G * PHI * Shc * FVF}_{\text{Accumulations (OIP/ GIP)}} * RF$$

- **GRV:** **Gross Rock Volume** (HC-bearing GRV)
- **N/G:** **Net-to-Gross** (ratio of volume and thickness)
- **PHI:** **Porosity** (Φ effective)
- **Shc:** **Hydrocarbon Saturation** (oil or gas)
- **FVF:** **Volumetric Factor** (contraction: oil - expansion: gas)
- **RF:** **Recovery Factor**
- **OIP/GIP:** **Oil / Gas In Place**

Deterministic evaluation

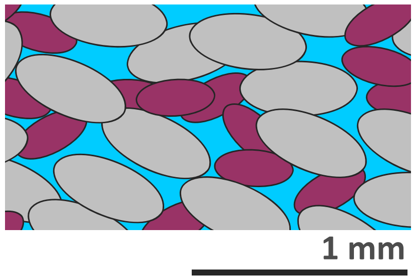


HC in place Volume = Bulk rock volume * Net / Gross * Porosity * Oil saturation * Formation volume factor

(Surface conditions)

HCIIP
OOIP
IGIP

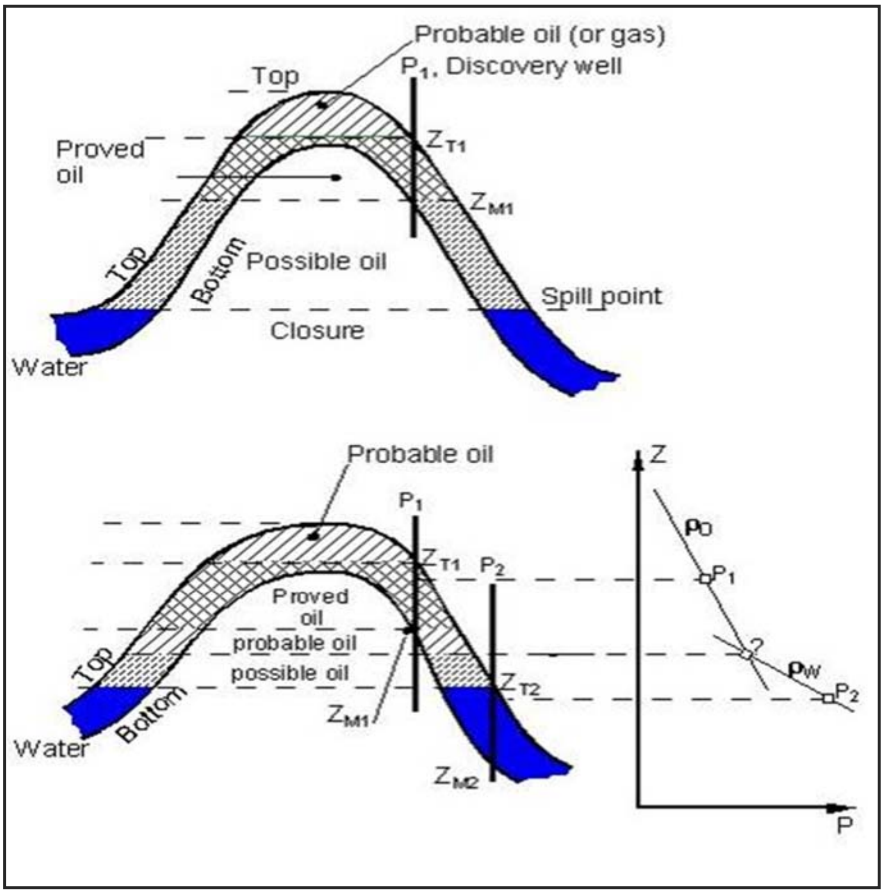
Bulk rock volume	BRV
*	
Net / Gross	N /G
*	
Porosity	ϕ
*	
Oil saturation	So
*	
Formation volume factor	1/Bo



$$\boxed{OHIP = BRV * N/G * \phi * So * (1/Bo)}$$

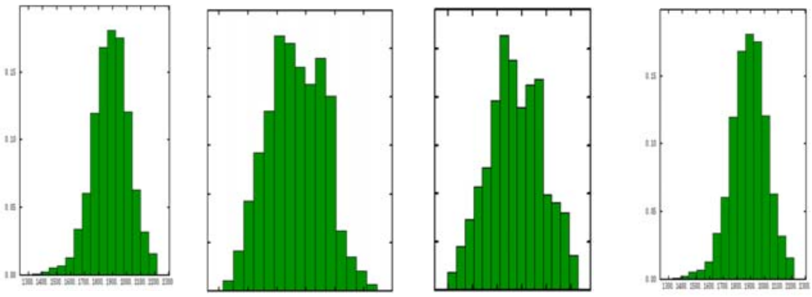
*OOIP reservoir = BRV reservoir above OWC * average (N/G) * average Phi * average So * average (1/Bo)*

Uncertaintiy on fluid contact geometry

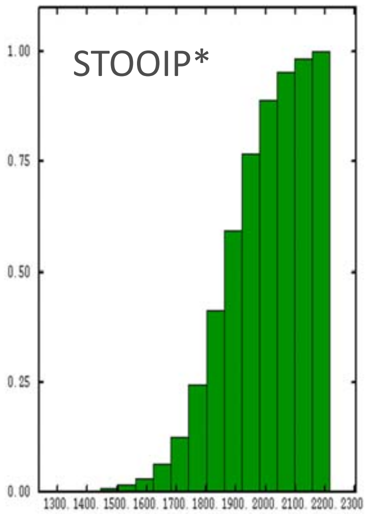


Probabilistic evaluation

GRV | N/G | Φ | Sw



"Monte-Carlo" simulation

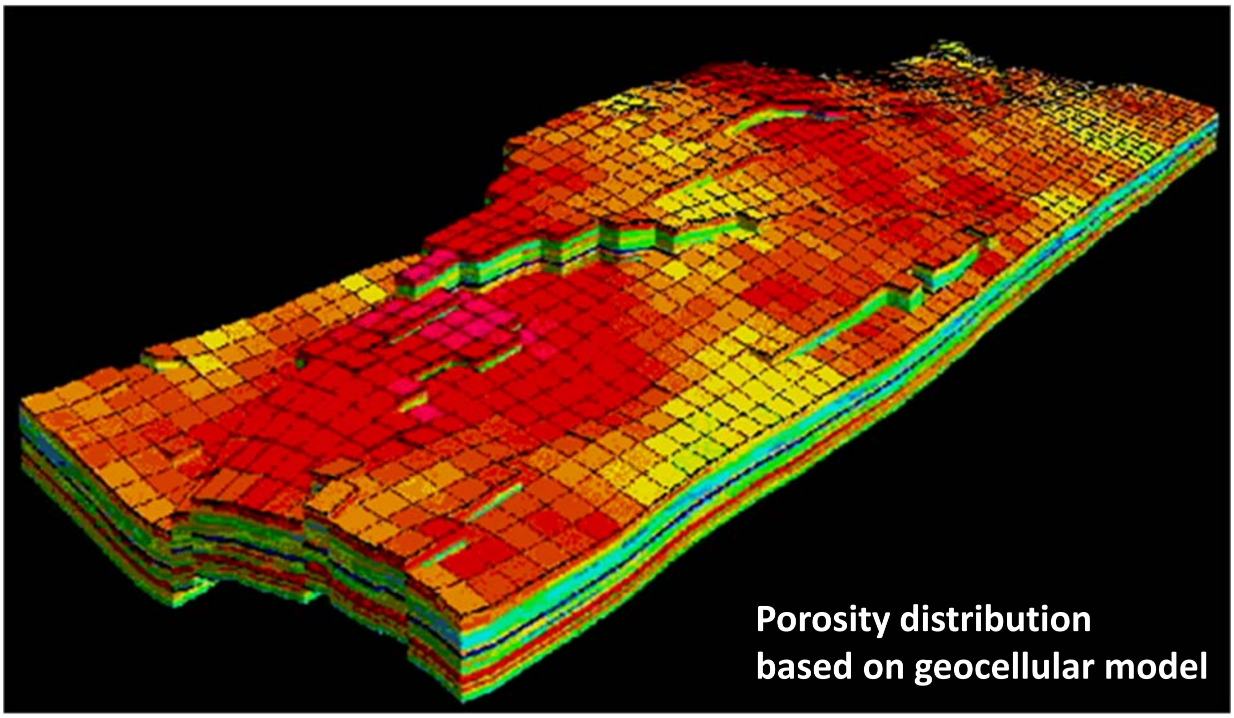


Random number generation

$$\text{STOOIP} = \frac{\text{GRV} \times \text{N/G} \times \Phi \times (1-\text{Sw})}{\text{Bo}}$$

STOOIP* = standard original oil in place

Probabilistic evaluation

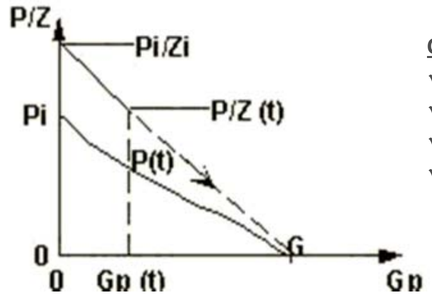


Dynamic evaluation

Material balance

Gas

Équation : $Gp = G\left\{1 - \left(\frac{Zi}{Pi} \cdot \frac{P}{Z}\right)\right\}$



Conditions:
- ✓No aquifer (We = 0)
- ✓Dry gas
- ✓No water injection
- ✓P > P saturation (Pr)

Gp = cumulative gas produced scf
G = free reservoir gas in place scf
Bg = gas formation volume factor
Z = compressibility factor

Oil

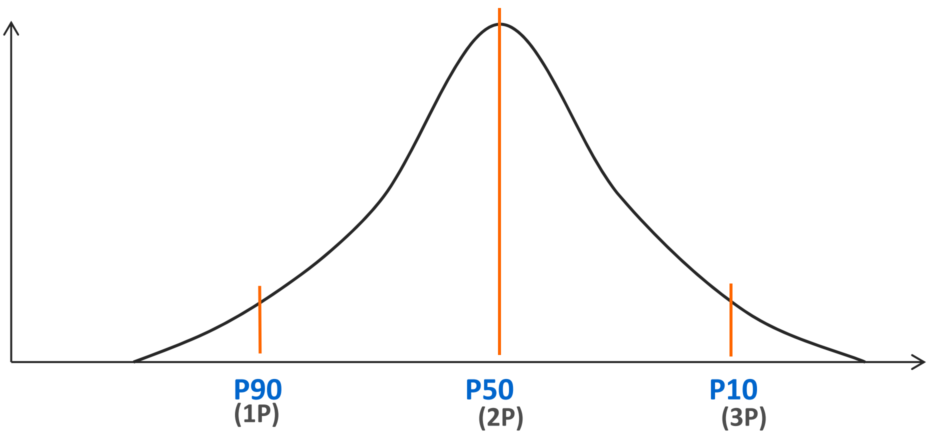
Équation : $NpBo = NBoi\ ce\ \Delta P$

Np = cumulative oil produced STB
N = reservoir oil in place STB
Bo = oil formation volume factor
Ce = effective compressibility =
= Co +(Cw.Sw/ So) + (Cf / So)
ΔP = pressure drop Pi - P

Conditions:
- ✓No aquifer (We = 0)
- ✓No gas cap
- ✓No water injection
- ✓P > P saturation (Pb)

Reserves evaluation

- **1P/2P/3P ranges**



From J.Pouzet

- **P90**: Value too low 90% of the time ➡ **"Proven" (1P)**
- **P50**: Value too low / too high 50% of the time ➡ **"Proven + Probable" (2P)**

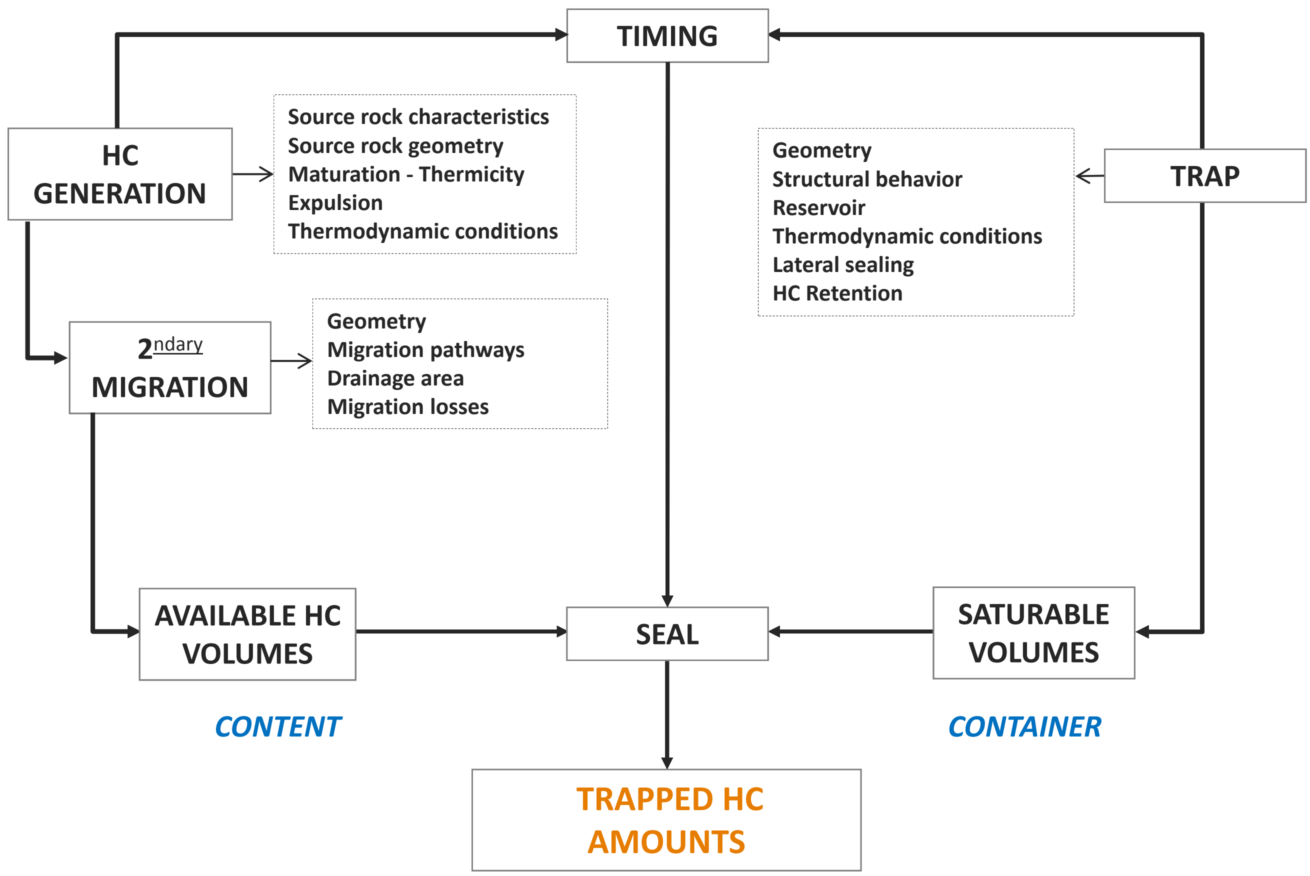
NB : in all practical cases, confusing P50 (median), the most likely value (mode) and the mean value is of no consequence

- **P10**: Value too low 10% of the time ➡ **"Proven + Probable + Possible" (3P)**

Volumetric estimation - Key points

- **Three methods**
  - Deterministic: for each category: Proven, Probable, Possible, OOIP estimated deterministically as a discrete volume (3 sets of reservoir parameter maps).
  - Probabilistic: provide a range of values rather than a single value. Three values: P90 for minimum, P50 for median and P10 for maximum.
  - Dynamic: material balance
- **Three categories**
  - Proven reserves: “1P”
    - Quantities of HC that will be produced
    - More than 90% reliable,
    - Official figure audited and published (annual report of listed companies)
    - Taken into consideration by financial community (SEC)
  - Proven and Probable: “2P”
    - More than 50% likely to be produced
    - Not published (companies’ strategic “secret”)
    - Taken into consideration for decision-making* and financing**
    - Probable reserves may become proven with improved knowledge of the field
  - Proven, Probable and Possible: “3P”
    - 10% reliability only on potential production
    - Not published, not considered

Basin HC potential assessment: a 4-dimension evaluation



Synchronisation entre les éléments et les processus

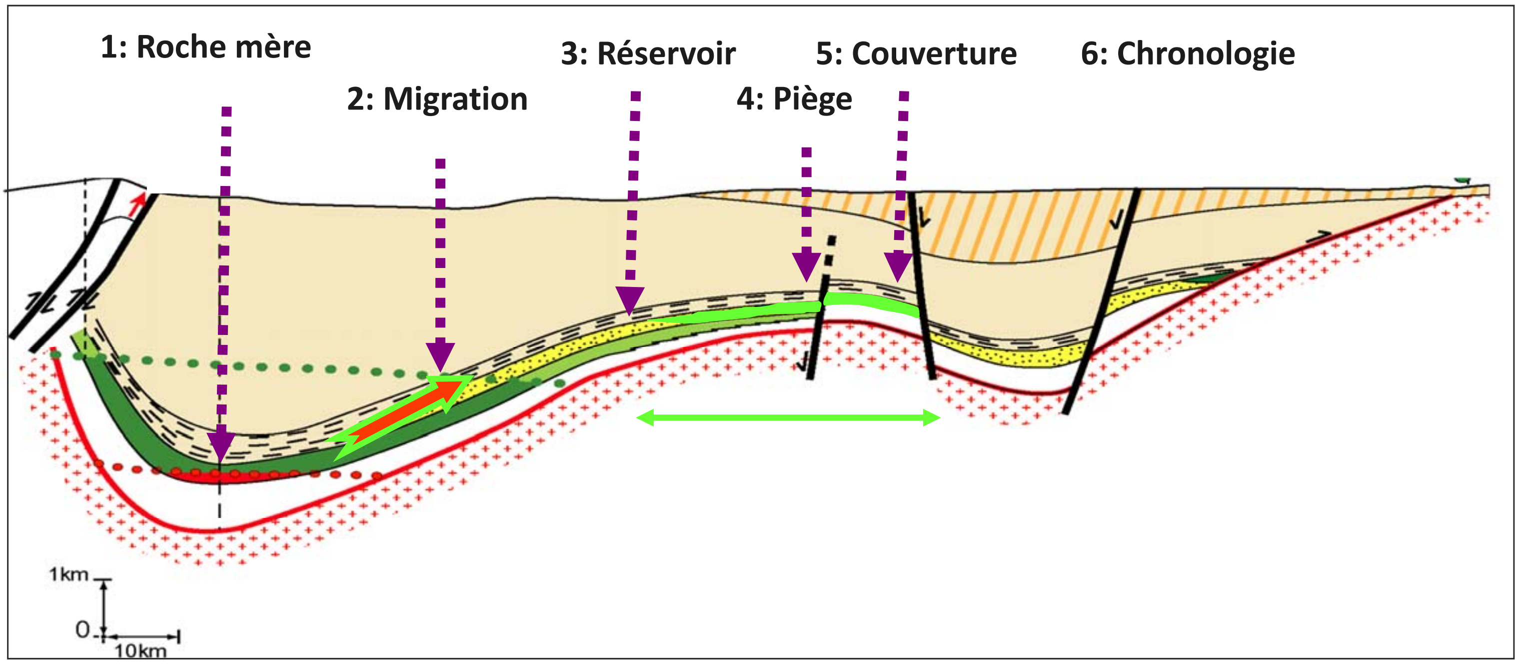
Le piège doit être disponible avant/pendant la migration

Piège

2. Processus : Génération → Migration → Accumulation et préservation

1. Éléments : Roche-mère | Chemins de migration | Réservoir et couverture

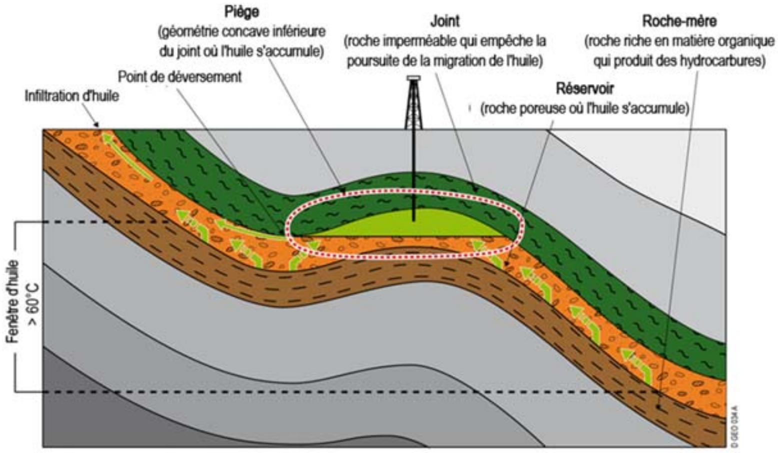
Vital pour l'explorateur : La clé du succès dépend de 6 paramètres



Si un de ces 6 paramètres n'est pas satisfait, c'est l'échec pour le prospect
La PS (probabilité de succès) est le produit des probabilités d'existence de chaque paramètre.

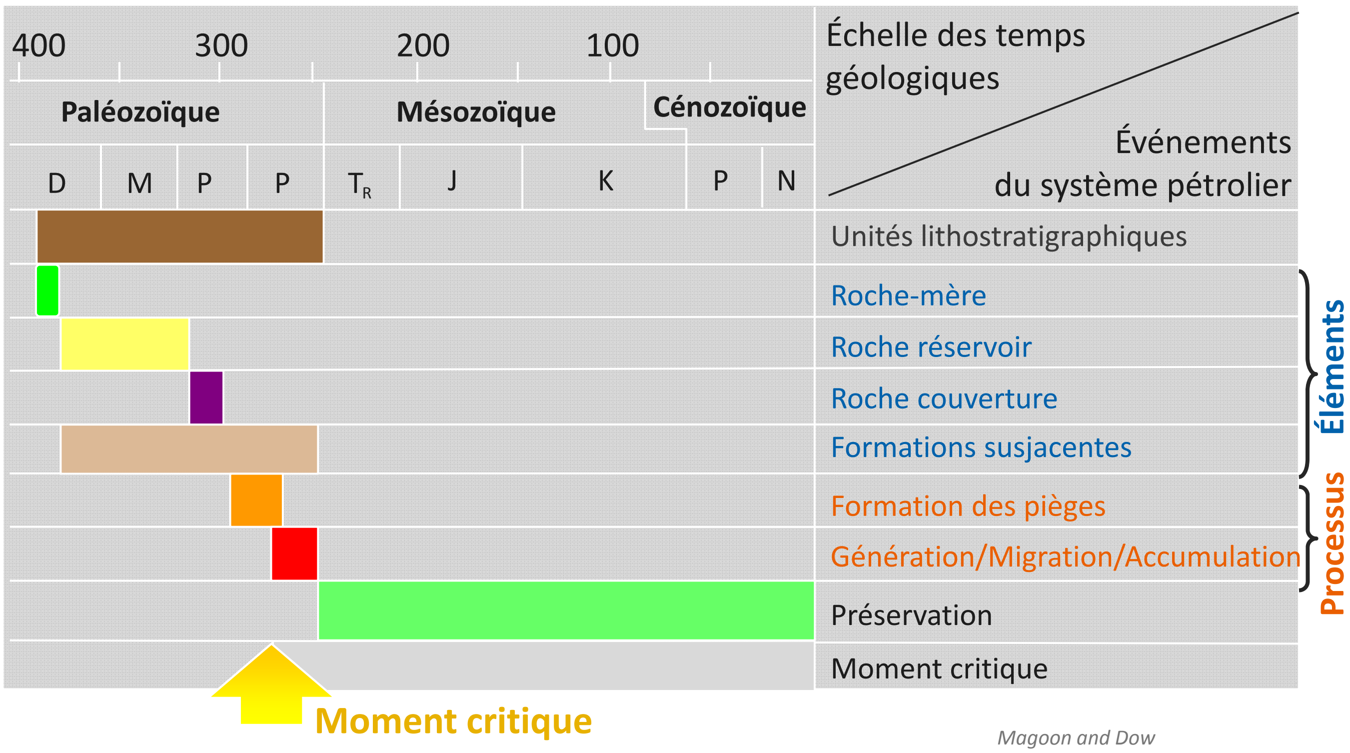
Conditions pour la formation d'un gisement d'hydrocarbures

- **Présence nécessaire de :**
  - une (ou plus) roche-mère mature,
  - une (ou plus) roche réservoir,
  - une roche couverture,
  - une phase (+chemins) de migration,
  - un (ou plusieurs) pièges,



… et :

- une chronologie adéquate entre la formation du piège, la génération d'hydrocarbures et les épisodes de migration
- des quantités suffisantes d'hydrocarbures pour alimenter le piège
- la préservation de l'intégrité du piège au cours des temps géologiques



Période d'expulsion et de migration
(les pièges doivent déjà exister)

Magoon and Dow

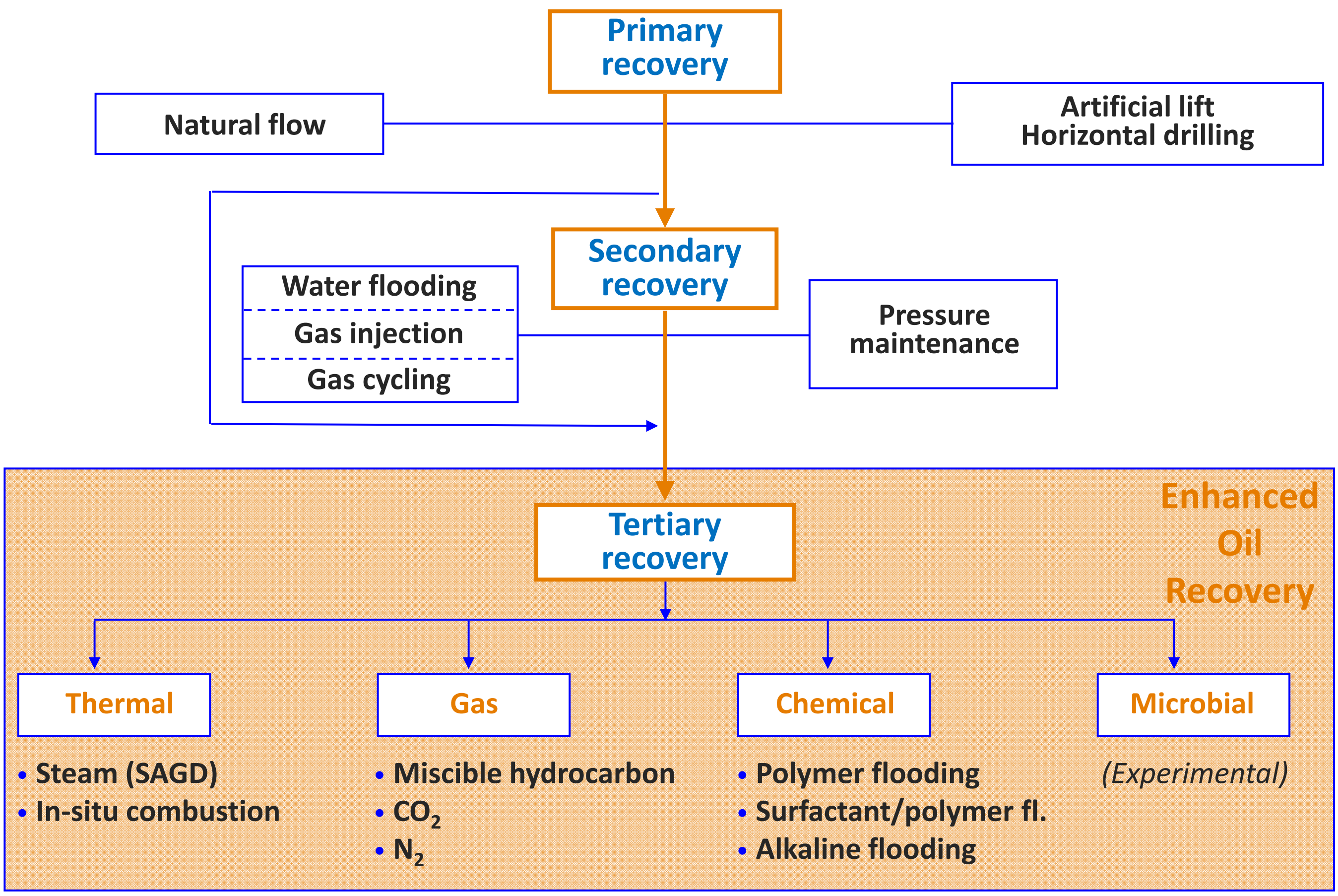
Notes

Notes

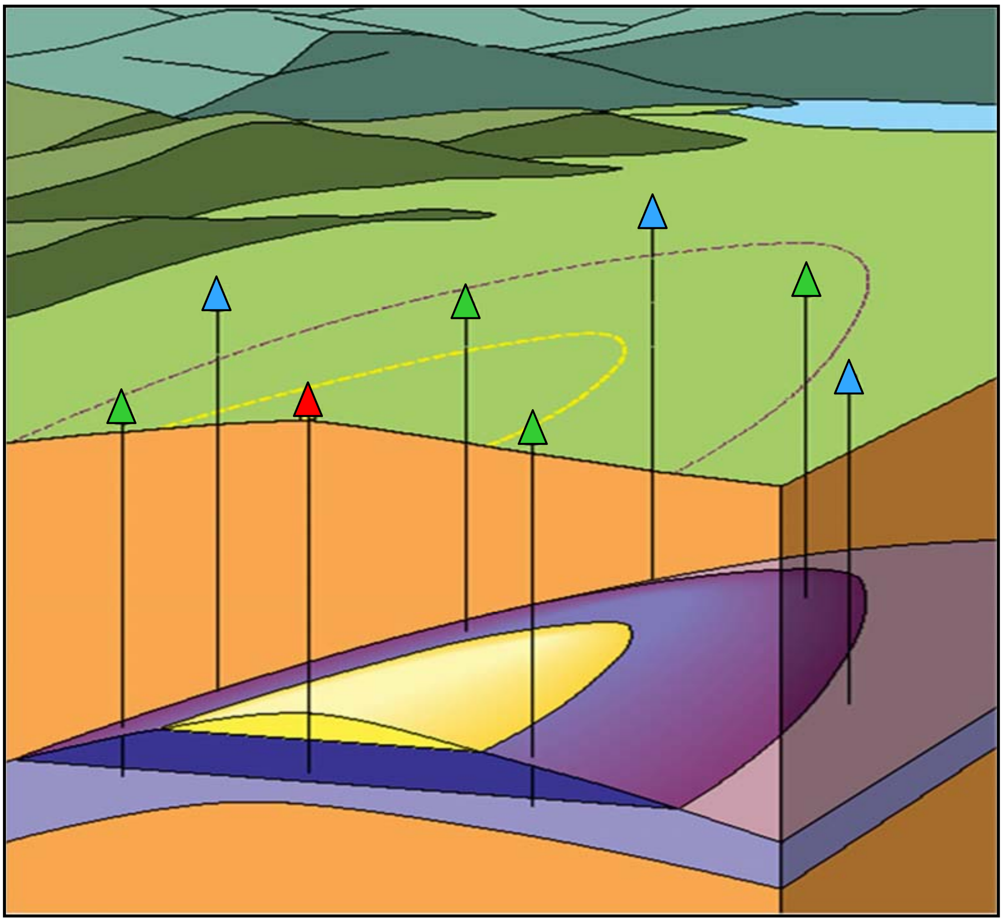
Volumetrics

- Estimation of in-place hydrocarbon accumulations
- Conventional hydrocarbon recovery

Recovery types



Field development strategy



Oil producer
Gas injector
Water injector

Behaviour of oil – Reservoir vs surface conditions

Surface conditions

Reservoir conditions

1 m³ of oil → **200 m³ of gas**

1 m³ of oil → **0.8 m³ of oil**

Formation Volume Factor for oil:
Bo = 1 / 0.8 = 1.25 m³/m³

Gas/Oil ratio:
GOR = 200 / 0.8 = 250 Sm³/m³

Behaviour of gas – Reservoir vs surface conditions

Surface conditions

Reservoir conditions

1 m³ of gas

200 m³ of gas

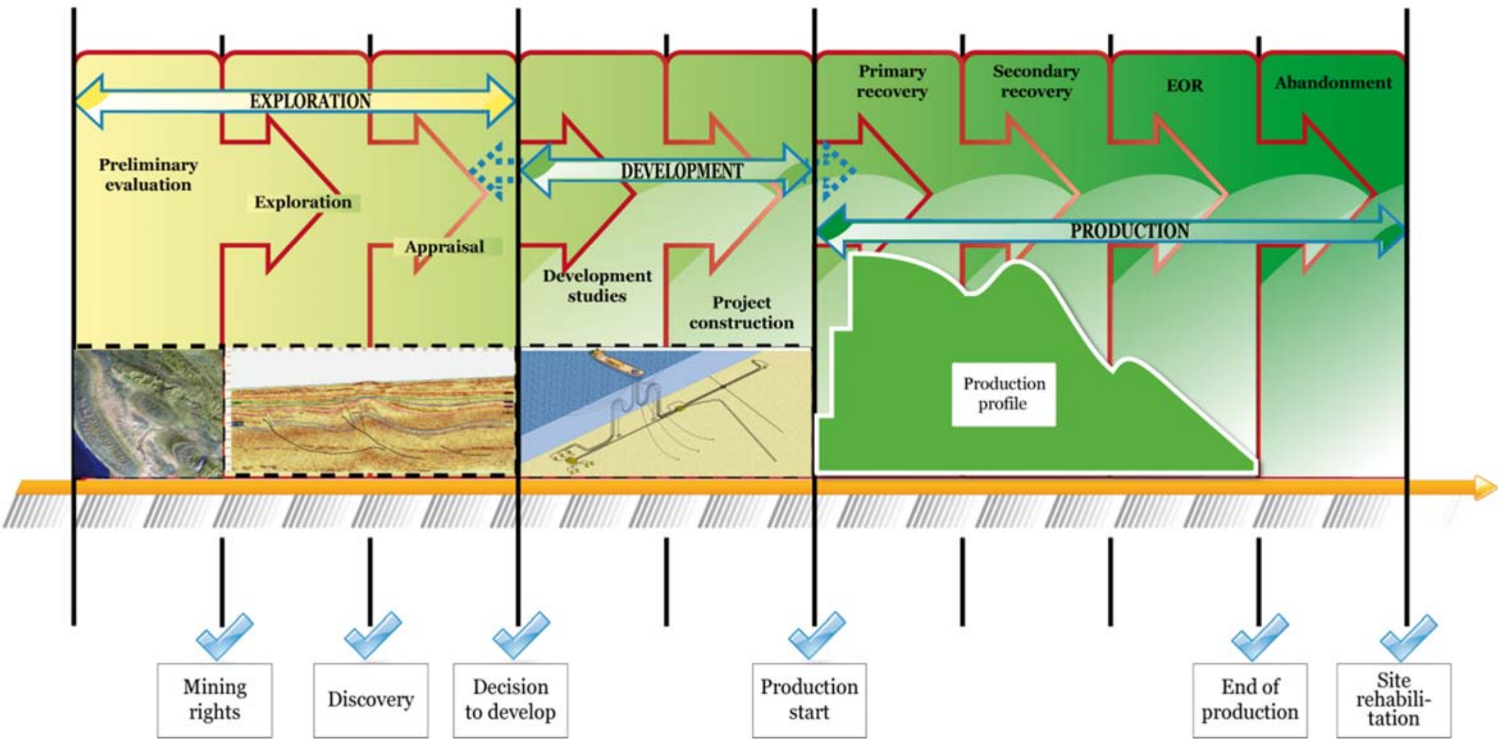
0.2 m³ of condensates

Formation Volume Factor for gas:
$Bg = 1 / 200\ m^3/m^3$

Condensate/Gas ratio:
$CGR = 0.2 / 200 = 0.001\ Sm^3/m^3$
$GOR = 1 / CGR = 1\,000\ Sm^3/m^3$

E & P workflow

Main phases of a field's life



Notes

Notes

Data consistency vs probability of success

Is there oil and where?

That is the question!

For the explorationist

Seal

Trap

Reservoir

Migration pathway

Source Rock

Timing

Preservation

...You win!

If ALL conditions are favorable

Integrity/leaks

Closure/fractures

Porosity/perm./size

Migration/dysmigration

Maturity

If only ONE answer is "NO"

...You loose!

Data, tools & uncertainties

GEOLOGICAL CONTEXT

TRAPS

MIGRATIONS

SEALS

RESERVOIRS

SOURCE ROCKS

BASIN DEFORMATION

BASIN SEDIMENTATION

ROCKS

PLATE TECTONICS

THE EARTH

Reservoir characterization and modeling

TOOLS USED

PRE-STUDY

GEOPHYSICS

WELL-SITE GEOLOGY

WIRELINE LOG

PROSPECT and ACCUMULATION EVALUATION

GEOMODELING

Data, tools & uncertainties

Uncertainties

Exploration

Shape

Static

Delineation

Reservoir characterization

Dynamic

Production

Fluids

Heterogeneities

GRV

N-to-G

Porosity

S_o

$1/B_o$

Plate tectonics

Passive margins, Foreland basins, Intracratonic margins

Tectonics

Extension, Compression

Salt, Mud

Rocks

Clastic, carbonates, salt

Diagenesis

Environment

Alluvial fan, braided rivers, meanders, littoral, dunes, platform, reef, deep sea fan, turbidites

Photos

Field

Seismic

Sedimentology

Stratigraphy

Mudlogging

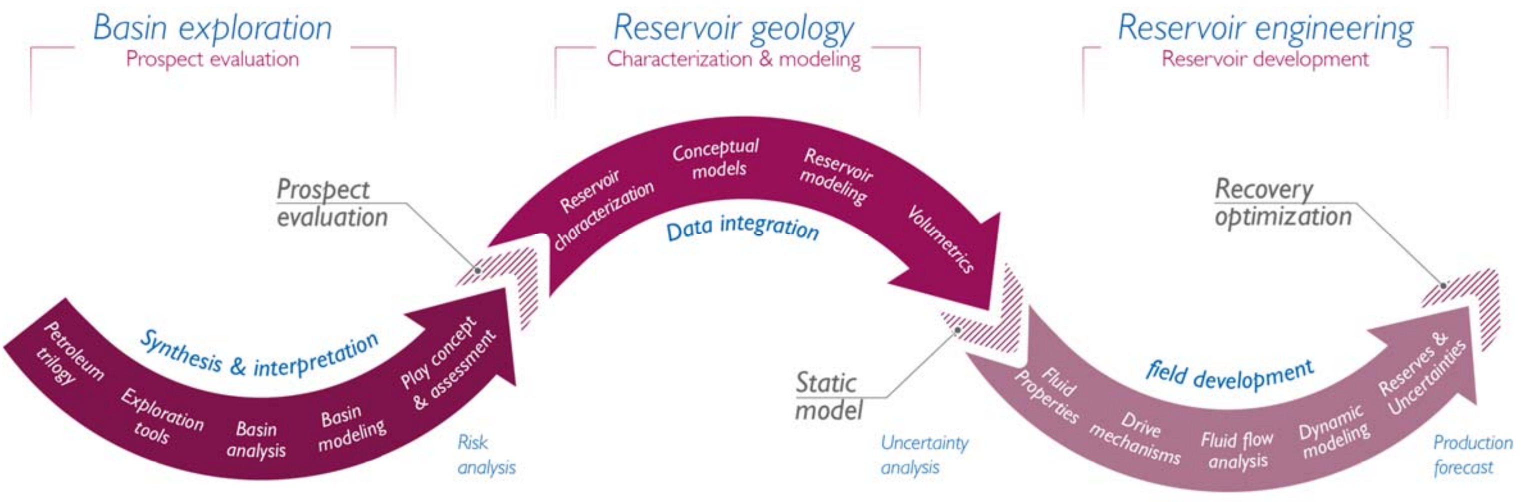
Sampling

Logs

Well testing

Thank you for your attention!

E&P Geosciences integrated workflows



Integrated programs:

> PetEx
- 3D Seismic interpretation
- Structural modeling
- Sequence stratigraphy
- Well log analysis
- Well geographysics / Borehole seismic
- Geochemistry
- Petroleum systems

> RCM
- Core description
- Well logs, electro-facies
- Core analysis, petrophysics
- Rock typing, rock properties
- Seismic facies
- Geostatistics
- Heterogeneities
- Fractured reservoirs

> ResEng
- PVT, fluid studies
- SCAL, petrophysics
- Well test analysis
- Dynamic reservoir simulation
- Optimized recovery EOR / IOR
- Development project and uncertainties

Notes

Notes